A HIGH FREQUENCY TRANSISTOR ANALYSIS

James Kenneth Keihner

A HIGH FREQUENCY TRANSISTOR ANALYSIS

* * * * * *

James K. Keihner

A HIGH FREQUENCY TRANSISTOR ANALYSIS

by

James Kenneth Keihner
Lieutenant, United States Navy

Submitted in partial fulfillment
of the requirements
for the degree of
MASTER OF SCIENCE
IN
ENGINEERING ELECTRONICS

United States Naval Postgraduate School
Monterey, California

1 9 5 6

This work is accepted as fulfilling

the thesis requirements for the degree of

MASTER OF SCIENCE

IN

ENGINEERING ELECTRONICS

from the

United States Naval Postgraduate School

PREFACE

The junction transistor was conceived by Shockley less than ten years ago, but already it has made giant strides in overtaking its much older rival, the vacuum tube.

The Philco Corporation discovered and patented the electrolytic etching process of constructing transistors [14]. This process uses a metallic salt to etch away material from each side of a basic slab of n-type germanium until only a very thin width remains between the etched regions. The width is determined accurately by measuring the intensity of infra-red light passing through the etched region. When the desired width is reached, the etching process is discontinued, and emitter and collector electrodes are electroplated in the etched areas by reversing the current used for etching. This process has been called the surface barrier technique of constructing transistors. By virtue of the surface barrier technique, the Philco Corporation has been among the leaders in the electronics industry in the construction of high frequency transistors.

Much of the experimental data and knowledge of transistors necessary in preparing this thesis was acquired during a ten week industrial tour by the writer at the Philco Corporation. The writer wishes to thank the many engineers in the Philco Research Division for their generous assistance in preparing this paper.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

TABLE OF SYMBOLS AND ABBREVIATIONS

r_e - Emitter Resistance

r_b - Base Resistance

r_c - Collector Resistance

C_c - Collector-Base Transition Layer Capacitance

r_m - Mutual Resistance

α - Short Circuit Common Base Current Amplification Factor

σ_n - Conductivity of n-type Region in Ohm-Cms

σ_p - Conductivity of p-type Region in Ohm-Cms

r_d - Forward Biased Emitter-Base Diode Resistance

r_r - Back Biased Collector-Base Diode Resistance

r_b' - Base Spreading Resistance

α' - Current Amplification Factor of the Intrinsic Alpha Generator

β - Transport Factor

γ - Emission Efficiency

μ_{rc} - Reverse Voltage Amplification Factor

r_s - Feedback Resistor between Collector and Emitter

C_{Te} - Emitter-Base Transition Layer Capacitance

C_{sr} - Surface Recombination Capacitance

C_N - Majority Carrier Capacitance

C_3 - Collector-Base Interelectrode Capacitance

$f_{c\alpha}$ - Emitter Cut-Off Frequency

$f_{c\alpha'}$ - Diffusion and Injection Cut-Off Frequency

f_{cc} - Collector Cut-Off Frequency

$f_{c\alpha}$ - Total Cut-Off Frequency

τ_B - Minority Carrier Lifetime in Base

τ_d - Diffusion Time of Minority Carriers

W - Base Width in Cms

D_p - Diffusion Constant for Holes

L_B - Diffusion Length in Base Region

ρ_b - Base Resistivity

ρ_e - Emitter Resistivity

ρ_c - Collector Resistivity

τ_e - Minority Carrier Lifetime in Emitter Region

n_e - Minority Carrier Density in Emitter Region in Carriers per Cubic Cm.

SBT - Surface Barrier Transistor

Zero Subscript - A zero subscript, such as β_o, refers to the low frequency value of the quantity.

CHAPTER I

INTRODUCTION

The past decade has seen the relatively rapid development of the transistor. Since the Bell Telephone laboratories announced the development of an elementary type of transistor in the July 15, 1948 issue of the Physical Review, the transistor has gained a position as a competitor to the vacuum tube. The transistor has not, and possibly will not, take over the position the vacuum tube enjoys in the electronics industry. The transistor, however, by its very nature has certain desirable characteristics which have led many industries to devote time and money to the study and development of transistors. These advantages include the following:

a) The transistor is very reliable; that is, under normal operating conditions the transistor has a longer useful life than the vacuum tube.

b) The transistor is small in size and light in weight.

c) The transistor requires little power to operate.

d) The transistor can stand more physical shock. In light of these characteristics it is very understandable why the Military Establishment has pushed the development of the transistor.

There have also been stumbling blocks in the fulfillment of the transistor's ultimate capabilities. Their disadvantages include the facts that:

a) The transistor has a relatively poor high-frequency response.

b) The germanium used in the transistor is very sensitive to temperature changes.

c) There are numerous problems when constructing transistors.

d) Transistors have relatively low power capabilities.

In this thesis the writer will start with a low frequency equivalent circuit, and from it develop in stages a high frequency equivalent circuit for Philco surface barrier PNP transistors. These stages of development will include the various factors which determine the frequency response of a transistor, with particular emphasis on the alpha generator. Finally, the writer will discuss the recent trends in high frequency transistor development.

CHAPTER II

LOW FREQUENCY EQUIVALENT CIRCUITS

1. General Discussion

A low frequency equivalent circuit for a transistor is made up of circuit components that are pure resistances. At low frequencies, any reactive component of a transistor may be neglected, since the value of its reactance is very high as compared with the resistance with which it is in shunt. Low frequency equivalent circuits formulated by logical reasoning from elementary knowledge of a transistor are shown in Figure 1 and Figure 2. Factors affecting frequency response in a transistor will be discussed in Chapter III.

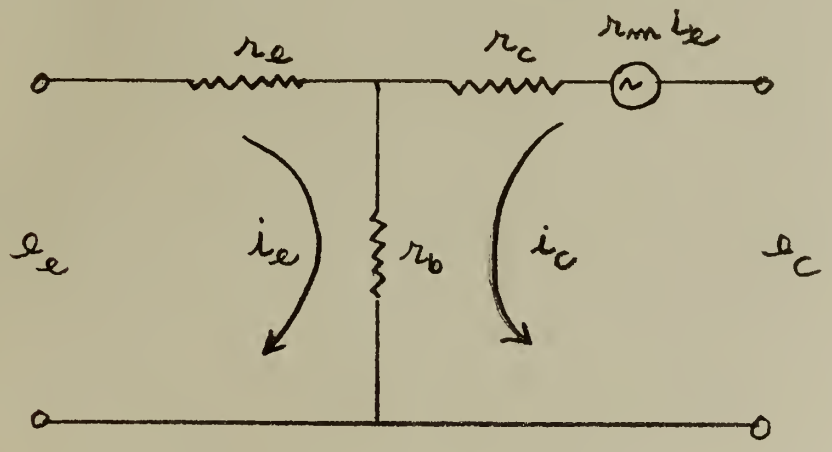


Figure 1

LOW FREQUENCY EQUIVALENT CIRCUIT

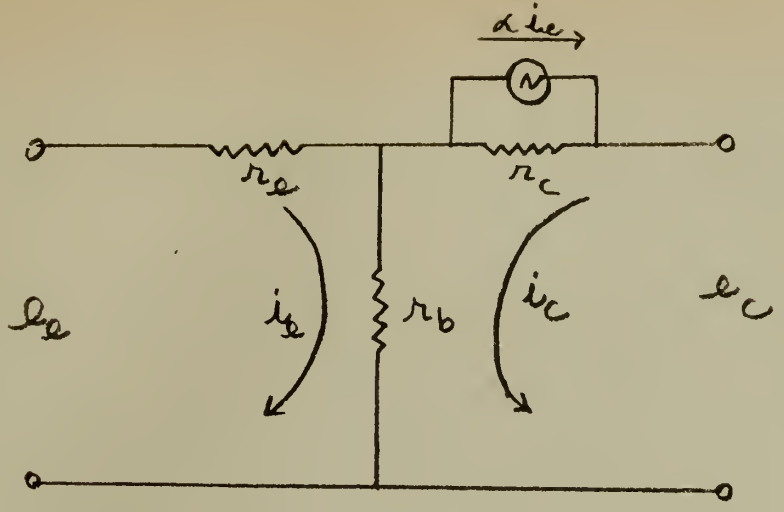


Figure 2

LOW FREQUENCY EQUIVALENT CIRCUIT

Equations representing the equivalent circuits shown in Figure 1 and Figure 2 are written below.

For Figure 1

$$\begin{cases} e_e = i_e (r_e + r_b) + i_c (r_b) \\ e_c = i_e (r_m + r_b) + i_c (r_c + r_b) \end{cases}$$

For Figure 2

$$\begin{cases} e_e = i_e (r_e + r_b) + i_c (r_b) \\ e_c = i_e (\alpha r_c + r_b) + i_c (r_c + r_b) \end{cases}$$

CHAPTER III

FACTORS AFFECTING FREQUENCY RESPONSE OF A TRANSISTOR

1. General Discussion

The factors that will be considered which affect the frequency response of a transistor are as follows:

1) The collector-base transition capacitance

2) Base width modulation

3) The emitter-base transition capacitance

4) The base spreading resistance

5) The parasitic effects

6) The alpha generator

Factors one through five will be discussed and incorporated in equivalent circuits in this chapter. The alpha generator is considered so important by the author that Chapter IV will be devoted to a treatment of it.

2. Collector-Base Transition Capacitance

The collector-base transition capacitance, C_c, is the capacitance of the $p-n$ junction between the collector and base regions of the transistor. In an equivalent circuit for a transistor, C_c is placed in parallel with the effective resistance, r_r, of the collector-base junction. Since this junction is biased in the reverse direction in a transistor, the magnitude of r_r is quite high. The value of r_r varies between 35,000 ohms and 500,000 ohms for a surface barrier transistor. The reactance of C_c must be several times the resistance of r_r before C_c may be neglected in an equivalent circuit. However,

the reactance of C_c may approach the resistance of r_v as the frequency is increased, and therefore, C_c should be included in the transistor's equivalent circuit. The equivalent circuit shown in Figure 3 includes C_c as one of its components.

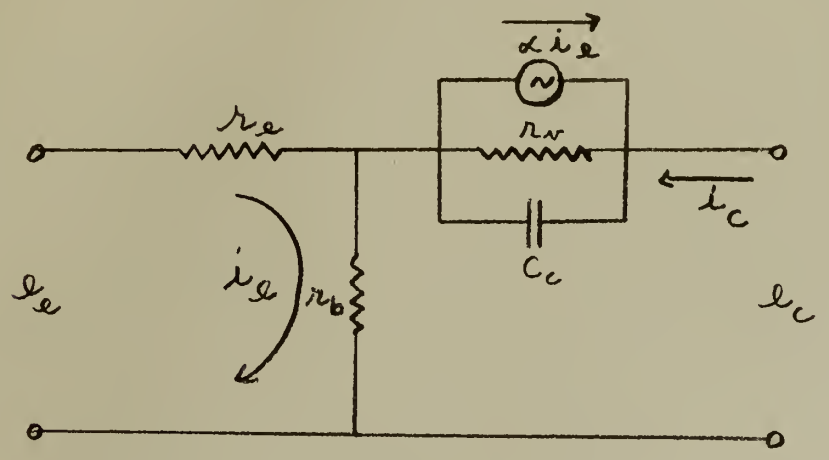


Figure 3

EQUIVALENT CIRCUIT INCLUDING C_c

3. Base Width Modulation

The only feedback term considered in Chapter II was due to r_b. However, another feedback term occurs due to base width modulation [3]. As i_c varies, the width of the base-collector region varies in a manner directly proportional to the square root of the collector-base voltage. The thickness, designated by t, of the collector-base transition region is given by the following formula [8].

$$t = A \sqrt{V\left(\frac{1}{\sigma_n} + \frac{1}{\sigma_p}\right)}$$

where A and b are constants, and V is the collector-base voltage.

The collector-base transition region width across the p-n junction will always extend farther into the region of higher resistivity. This statement may be understood if one considers that an electric line of force connects each ionized donor and acceptor atom on different sides of the p-n junction. Thus, if the base region has a higher value of resistivity than the collector region, that is if the density of the donor atoms is less in the base than the density of the acceptor atoms in the collector, then the lines of force must extend relatively far into the base region as compared to the collector region. A typical value of base resistivity for Philco high frequency transistors is .01 ohm-cms as compared to the collector resistivity of .001 ohm-cms. Since the base region has a higher value of resistivity than the collector region, it follows that any change in t with V shows up predominantly as a change in effective base width. This effect is known as base-width modulation.

A decrease in base layer thickness has two principal effects. First, it decreases the recombination of minority and majority carriers in the base region, thus increasing the magnitude of α. The second effect is to decrease the impedance presented to the minority carrier current by the emitter. These two effects constitute feedback from the collector to the emitter circuit. The input impedance presented to the minority carrier current depends on base-layer resistivity and base-layer thickness. J. M. Early of Bell Laboratories showed that a decrease of base-layer width reduced the resistance to the injection of minority current carriers into the base by the emitter [3].

Base width modulation occurs at all frequencies, and its value increases nonlinearly with frequency. It may be neglected at very low frequencies, however, since at these frequencies its absolute magnitude is small. At high frequencies its effect is reduced by the increased current feedback through r_b, but it is of enough importance to consider it in a high frequency equivalent circuit.

J. M. Early first incorporated the effect of base width modulation in an equivalent circuit by placing a feedback voltage generator of value $\mu_{ec} e_c'$ in series with the emitter resistance [3], where:

$$\mu_{ec} = \left.\frac{\partial V_e}{\partial V_c}\right|_{I_e}$$

e_c' is the voltage as indicated in Figure 4.

The lumped device parameters will be designated as r_e, r_b', r_v, and C_c. These parameters are defined in the table of symbols. Early's equivalent circuit is shown in Figure 4.

In Figure 4, r_b' is the base spreading resistance, which is the resistance of the bulk material in the base region to current flow. The effect of base width modulation on the magnitude of r_b' is normally negligible because the portion of r_b' outside of the active region of the transistor is large, and the magnitude of r_b' is thus unaffected by base width modulation [8].

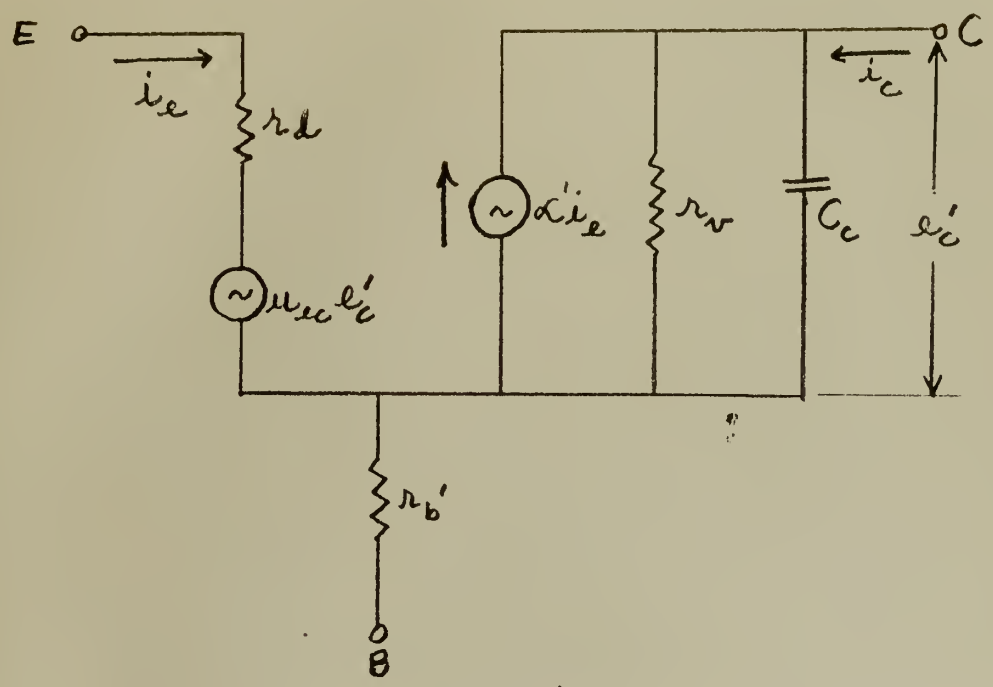


Figure 4

EARLY'S EQUIVALENT CIRCUIT

F. Keiper of the Philco Corporation devised another method of incorporating base width modulation in an equivalent circuit. Keiper placed a resistance, r_s, between the collector and the emitter; thus giving a feedback path to the emitter. This resistance will feed back a portion of the output voltage to the input circuit. Keiper's equivalent circuit is shown in Figure 5 [10]. Normally, the magnitude of r_s is of the order of 500 times as large as that of r_d.

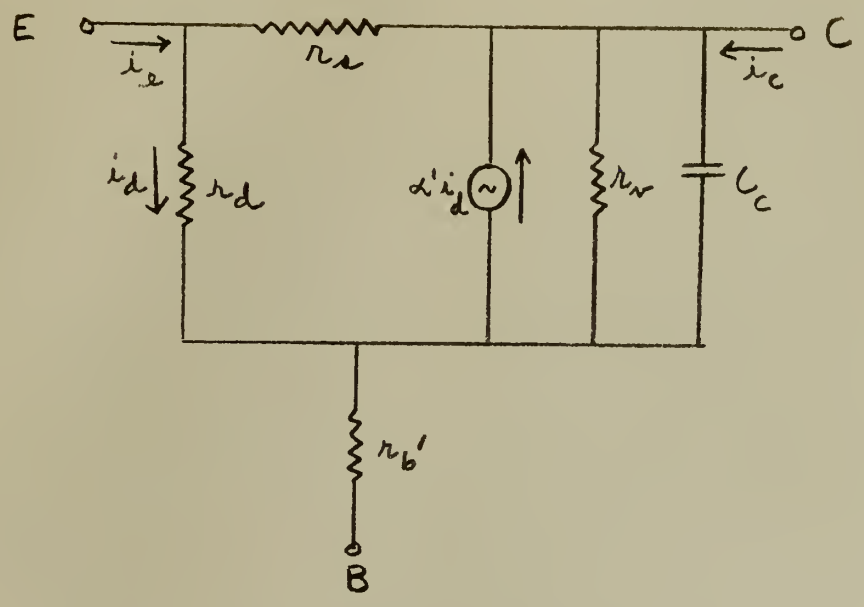


Figure 5
KEIPER'S EQUIVALENT CIRCUIT

4. Emitter-Base Transition Layer Capacitance, C_{Te}

Thus far in this discussion C_{Te} has been neglected because it is in parallel with the relatively small resistance r_d. However, at higher frequencies the reactance of C_{Te} becomes comparable to the magnitude of r_d, and therefore the effect of C_{Te} becomes significant.

It is believed that the value of C_{Te} is in the order of ten to one hundred times as large as that of C_c [6,8]. This is because the bias voltage is relatively small across C_{Te}, and the emitter resistivity is normally less than the collector resistivity. C_{Te} varies with bias voltage, and also varies with the p and n type region resistivities as shown in the following formula [8].

$$C_{Te} \propto \frac{1}{\sqrt{(b\rho_n + \rho_p)V}}$$

where b is a constant.

C_{Te} is incorporated in the equivalent circuit shown in Figure 6.

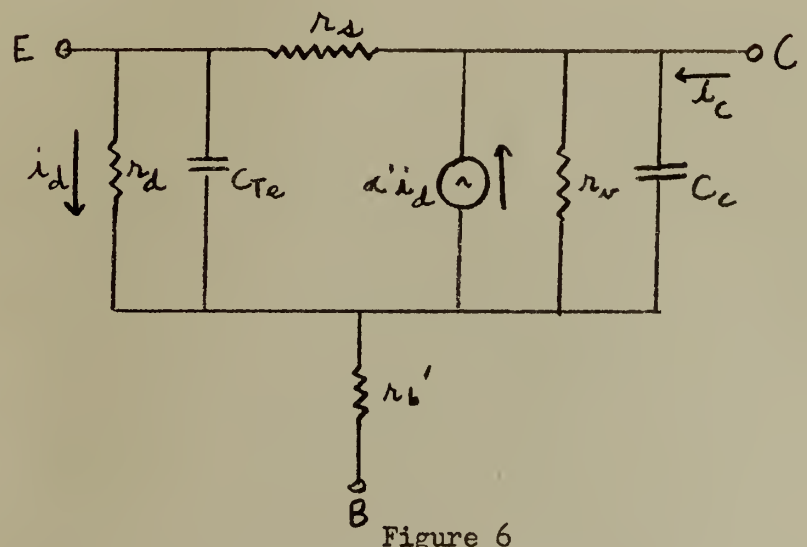


Figure 6

EQUIVALENT CIRCUIT INCLUDING C_{Te}

5. Base Spreading Resistance, r_b'

Base spreading resistance has been treated as non-reactive in the previous discussion. R. L. Pritchard, of the General Electric Corporation, in a paper on "Theory of Grown-Junction Transistors at High Frequencies," presented at the Semiconductor Device Research Conference, Minneapolis, Minn., 29 June 1954, stated that when analyzing a two-dimensional model applicable for a grown-junction type of construction, the ohmic base resistance, r_b', may be replaced by a complex frequency-dependent impedance. In experimental work done by this writer with

surface barrier transistors, r_b' was found to be a pure resistance. Consequently, r_b' will be treated in this paper as a pure resistance. The author believes that the reason why r_b' is a pure resistance in a surface barrier transistor is that the portion of the base region outside of the active area of the transistor is very large for a surface barrier transistor as compared with a grown-junction transistor.

6. Parasitic Effects

Parasitic effects in a PNP transistor refer to secondary effects usually of small consequence in the action of a transistor except at extremely high frequencies. Parasitic effects include surface recombination admittance, Y_{SR}, majority carrier admittance, Y_N, interelectrode capacitance, C_g, and emitter lead length inductance, L_e.

Majority carrier admittance, Y_N, [16] is the factor present at both the emitter-base junction and the collector-base junction which takes into account the effect of the unwanted electron flow through each junction. A capacitance, C_{Ne}, will be used to represent the susceptance part of Y_N. A capacitance may be used since the majority current carriers drifting across the junction areas in a transistor affect the space charge of the junction regions in the same manner as do the minority carriers, whose effect is represented by a capacitor.

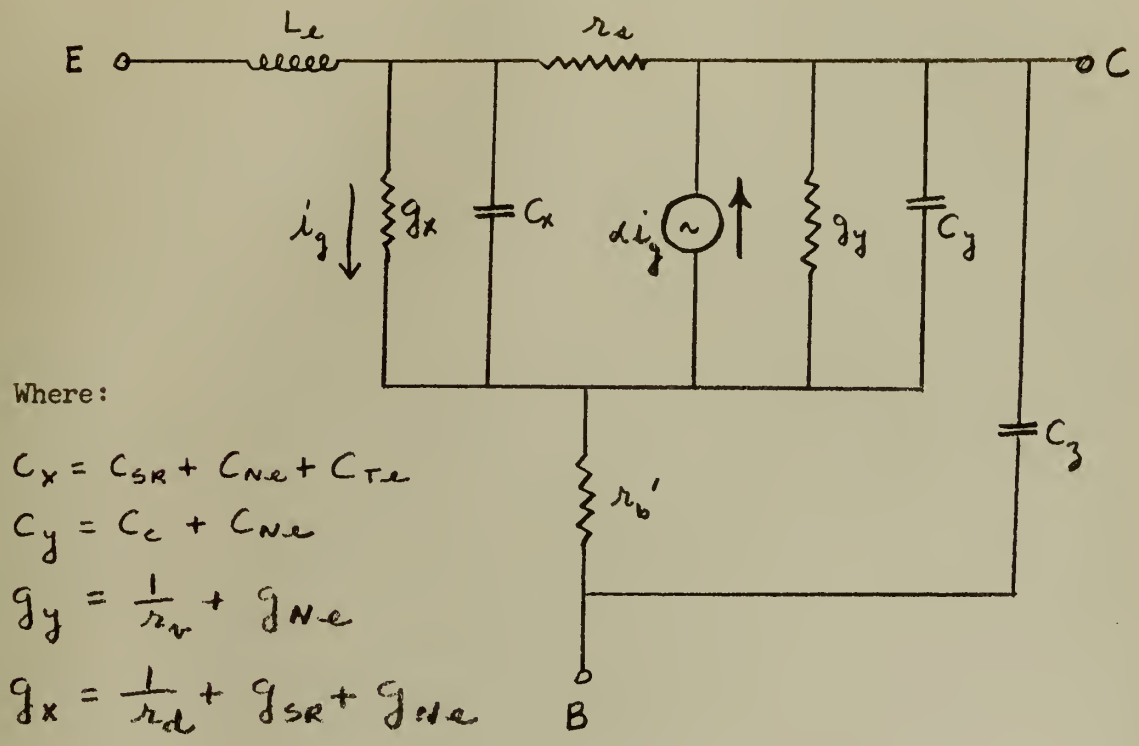
Surface recombination admittance, Y_{SR}, is a factor determined by the recombination of minority carriers at the surface of the crystal, in the vicinity of the emitter-base p-n junction. A lengthy expression has been developed for Y_{SR}, [8]. This expression is abbreviated as follows:

$$Y_{SR} = \left[f(I_E, V_E, T) \right] \left[1 + j\omega\tau_B \right]^{1/2}$$

where $f(I_E, V_E, T)$ is a real function of emitter-base voltage, of the absolute junction temperature in degrees Kelvin, and the emitter-base current. τ_B is the minority carrier lifetime in the base region. By analyzing the previous complex expression for Y_{SR}, it is apparent that surface recombination susceptance, being a positive function, may be represented by a capacitance in an equivalent circuit. This capacitance will be placed across the emitter-base junction capacitance since surface recombination takes place at the emitter-base junction.

Interelectrode capacitance, C_z, is the actual physical capacitance between the base and the collector electrodes. A similar capacitance exists between all electrodes of a transistor; however, the magnitude of all interelectrode capacitances except C_z are small enough to be negligible when formulating an equivalent circuit.

Emitter lead length inductance, L_e, is the inductance of the emitter lead of the transistor. L_e is approximately .01 μh ($\frac{1}{2}$" of three mil wire). Collector and base lead inductances may be neglected since the base contact is a flat surface, and does not exhibit any inductive effect, while the collector lead is made short enough and of large enough diameter so that its inductance is negligibly small. Figure 7 shows an equivalent circuit of a transistor including circuit elements which account for parasitic effects.



Where:

$C_x = C_{SR} + C_{Ne} + C_{Te}$

$C_y = C_c + C_{Ne}$

$g_y = \frac{1}{r_v} + g_{Ne}$

$g_x = \frac{1}{r_d} + g_{SR} + g_{de}$

Figure 7

EQUIVALENT CIRCUIT INCLUDING PARASITIC EFFECTS

CHAPTER IV

AN ANALYSIS OF THE ALPHA GENERATOR

1. General Discussion

The alpha generator will now be discussed in some detail. Originally alpha (α) was defined as the common-base configuration, short-circuit current amplification factor. There are three factors any one of which individually, or any combination of which jointly could reduce the magnitude and change the phase of α. These are the following:

1) The emitter time constant circuitry

2) The emission and diffusion of minority carriers into and across the base region, respectively

3) The collector time constant circuitry

2. Emitter Time Constant Circuitry

The emitter time constant circuitry involves the emitter transition capacity, C_{Te}, and the resistances composed of r_d and r_b'. Since C_{Te} is shunting a relatively low resistance in r_d, that current which flows through C_{Te} will not enter into the diffusion process, but rather will be bypassed to the base inactive region. At low frequencies C_{Te} bypasses only a negligible amount of current, but at a high enough frequency such that the reactance of C_{Te} equals r_d, a point is reached where the power gain of the transistor is cut to one-half of its d-c value by the emitter time constant circuitry alone. If r_b' is small enough to be of the same order of magnitude as r_d, then r_b' in conjunction with r_d must be taken into account in computing the time constant of the emitter circuitry. The frequency at which the reactance

of C_{Te} equals the effective resistance of r_d and/or r_b' is known as the emitter cut-off frequency, f_{ce}. The emitter cut-off frequency may be improved by reducing C_{Te}, r_d, and/or r_b' to lower the emitter time constant. However, decreasing one factor often increases another, and a compromise must be reached. For example, increasing ρ_B, decreases C_{Te} but increases r_b' [8]. Using presently assumed valid typical values for C_{Te}, r_d, and r_b', f_{ce} may be computed to be 140 mc. This computation is shown below.

$$C_{Te} = 40 \text{ mmf}$$
$$r_d = 27 \Omega$$
$$r_b' = 100 \Omega$$
$$f_{ce} \approx \frac{1}{2\pi C_{Te} r_d}$$
$$f_{ce} \approx \frac{1}{2\pi(40)(10^{-12})(27)}$$
$$f_{ce} \approx 140 \text{ mc}$$

3. Intrinsic Alpha Generator

The intrinsic alpha generator, α', is composed of two distinct factors. They are the emission efficiency, γ, and the transport factor, β. γ equals the ratio of the rate of injection of minority charge carriers into the base to the sum of the rate of minority charge carriers injected into the base plus the rate of majority charge carrier flow from base to emitter. γ may be treated as non-frequency dependent providing C_{Te} is considered part of the emitter circuitry and not a factor entering into γ [11,12,13]. Usually γ is made very close to one, in the order of .99, by doping the emitter region much more heavily than the base region [9].

The transport factor, β, is defined as the rate of minority charge carriers injected into the base to the rate of minority carriers arriving at the collector region. β is frequency dependent because of the basic nature of the diffusion process [9]. The frequency at which the charge carrier current has been reduced to .707 of its original magnitude and shifted by 45 degrees in phase from its low frequency value, due to the diffusion process in the base region alone, is known as $f_{c\alpha'}$. The magnitude of β is also reduced at all frequencies by the recombination of holes and electrons in the base region during diffusion of the holes.

The diffusion equation will now be analyzed to derive an expression for $f_{c\alpha'}$ and α'. Steele, of Bell Laboratories, showed that by setting up an equation for diffusion of minority carriers through the base region and by arithmetic manipulation, α' may be expressed by the following formula [4]:

$$\alpha' = \left\{ \operatorname{sech}\left[(1+j\omega\tau_B)^{1/2} \frac{W}{L_B} \right] \right\} \left\{ \frac{1}{1+\left(\frac{D_n}{D_p}\right)\left(\frac{n_e}{\rho_B}\right)\left(\frac{W}{L_E}\right)} \right\} = \beta\gamma$$

Assuming γ non-frequency dependent and high in the order of .99 or so, then

$$\alpha' = \beta = \operatorname{sech}\left[(1+j\omega\tau_B)^{1/2} \frac{W}{L_B} \right]$$

At sufficiently low frequencies such that

$$(\omega\tau_B)^2 \ll 1$$

then

$$\beta = \beta_o = \operatorname{sech} \frac{W}{L_B}$$

Where: β_o low frequency value of β

But for a good transistor $\left(\frac{W}{L_B}\right)^2 \ll 1$ so that

$$\beta_o = 1 - \frac{1}{2}\left(\frac{W}{L_B}\right)^2 \approx 1$$

Under the assumption that $\beta_o = 1$, the frequency variation of $\beta = \frac{\alpha'}{\alpha_o'}$ and may be expressed as

$$\frac{\alpha'}{\alpha_o'} = \beta = \operatorname{sech}(j\omega\tau_d)^{1/2}$$

Where:

$$\tau_d = \frac{\tau_B W^2}{L_B^2} = \frac{W^2}{D_p}$$

Where:

$$D_p = \frac{L_B^2}{\tau_B}$$

At an angular frequency $\omega_{c\alpha'}$ such that $\omega_{c\alpha'}\tau_d$ equals 2.43, $|\beta|^2$ equals 1/2 and $|\alpha'|$ will be down three db below its low frequency value. This indicates that the value of $f_{c\alpha'}$ is:

$$f_{c\alpha'} = \frac{2.43\, D_p}{2\pi W^2}$$

A typical value for $f_{c\alpha'}$ using high frequency experimental transistors is 2940 mc. The computation of this value is shown below.

$\rho_B = .01$ ohm-cms

$W = .2 \times 10^{-4}$ inches

$$D_p = \frac{KT}{q}\mu_p = .025 \times 760 = 19 \frac{cm}{sec}$$

$$f_{c\alpha'} = \frac{(2.43)(19)}{2\pi (.2\times10^{-4})^2 (2.54)^2}$$

$$f_{c\alpha'} = 2940 \text{ mc}$$

For frequencies small as compared to $\omega_{c\alpha'} = \frac{2.43}{\tau_D}$, the hyperbolic secant may be approximated by the first few terms of its power series expansion. Thus

$$\frac{\alpha'}{\alpha_o'} = \beta = 1 - j\frac{1}{2}\left(2.43\ \frac{\omega}{\omega_{c\alpha'}}\right) - \frac{5}{4!}\left(2.43\ \frac{\omega}{\omega_{c\alpha'}}\right)^2$$

Using only the first term for β

$$\alpha' = \alpha_o'\left(1 - j\,1.21\ \frac{\omega}{\omega_{c\alpha'}}\right) \approx \frac{\alpha_o'}{1 + j\,1.21\ \frac{\omega}{\omega_{c\alpha'}}}$$

Or approximately

$$\alpha' = \frac{\alpha_o'}{1 + j\ \frac{\omega}{\omega_{c\alpha'}}} = \frac{\alpha_o'}{1 + j\ \frac{f}{f_{c\alpha'}}}$$

The above expression for α' has been derived for frequencies small as compared with $f_{c\alpha'}$. Since $f_{c\alpha'}$ is in the order of 2940 mc for high frequency Philco experimental transistors, the formula derived for $f_{c\alpha'}$ applies with reasonable accuracy up to 1000 mc.

4. Collector Time Constant Circuitry

The collector time constant circuitry has the same effect on charge carriers entering its region as did the emitter time constant circuitry. The collector time constant circuitry is composed of C_c, r_b', and r_v. Since r_b' is much smaller than r_v its effect is predominate in forming a time constant with C_c. The cut-off frequency due to the emitter time constant is known as f_{cc}. The frequency, f_{cc}, at which the reactance of C_c equals r_b' is given by the following formula:

$$f_{cc} = \frac{1}{2\pi\, C_c\, r_b'}$$

A typical value for f_{cc} using Philco high frequency experimental transistors is computed below.

$$f_{cc} = \frac{1}{2\pi C_c r_b'}$$

$$C_c = 2\mu\mu f$$

$$r_b' = 100\ \Omega$$

$$f_{cc} = \frac{1}{(6.28)(2)(10^{-12})(100)}$$

$$f_{cc} = 530\ mc$$

In the above computation, a value for f_{cc} has been derived assuming the transit time of minority carriers through the collector-base depletion layer is negligible.

5. Comparison of Cut-Off Frequencies

Of the three cut-off frequencies, i.e., f_{ce}, $f_{c\alpha'}$, and f_{cc}, the one which is lowest is f_{ce}, whose value computes to be 140 mc. The three cut-off frequencies have been derived using the common base configuration. If the common emitter configuration is used, then all three cut-off frequencies are reduced by the factor $(1-\alpha_o')$. A proof of this statement follows. Let the common base cut-off frequencies corresponding to f_{ce}, $f_{c\alpha'}$, and f_{cc} be designated as f_e, $f_{\alpha'}$, and f_c, respectively. Also let the current generator for the common emitter configuration be designated as E. Then

$$E = \frac{\alpha}{1-\alpha}$$

but $$\alpha = \frac{\alpha_o'}{1+j\frac{f}{f_{c\alpha'}}}$$

Substituting for α

$$E = \frac{\frac{\alpha_o'}{1+j\frac{f}{f_{c\alpha'}}}}{1-\frac{\alpha_o'}{1+j\frac{f}{f_{c\alpha'}}}} = \frac{\alpha_o'}{1-\alpha_o'+j\frac{f}{f_{c\alpha'}}}$$

or

$$E = \frac{\frac{\alpha_o'}{1-\alpha_o'}}{1+j\frac{f}{f_{c\alpha'}(1-\alpha_o')}}$$

Therefore

$$E = \frac{E_o}{1+j\frac{f}{f_{c\alpha'}(1-\alpha_o')}}$$

The cut-off frequency for E in the formula derived above is equal to $f_{c\alpha'}(1-\alpha_o')$. Therefore $f_{c\alpha'}(1-\alpha_o')$ equals $f_{\alpha'}$. A relation for f_e and f_c in terms of f_{ce} and f_{cc} will be derived by an indirect method. The low frequency input impedance for the common base short-circuited output configuration of a surface barrier transistor equals $r_d+r_b'(1-\alpha_o')$ The low frequency input impedance for the common emitter short-circuited output configuration equals $r_b'+\frac{r_d}{1-\alpha_o'}$. Thus, the circuit elements r_d and r_b' are effectively increased in the common emitter configuration as compared with the common base configuration by the factor $\frac{1}{1-\alpha_o'}$. This phenomenon increases the values of the emitter and collector time constants of the common emitter configuration by the factor $\frac{1}{1-\alpha_o'}$ over those of the common base configuration. Therefore it follows that

$$f_{ce}(1-\alpha_o') = f_e \quad \text{and} \quad f_{cc}(1-\alpha_o') = f_c$$

6. Incorporating the Frequency Response of the Alpha Generator into Equivalent Circuits

Now that a frequency dependent expression has been developed for α', it will be possible to represent α' by a non-frequency dependent current generator and a suitable choice of lumped constants. F. Keiper of the Philco Corporation showed that this could be done for the equivalent circuit shown in Figure 8.

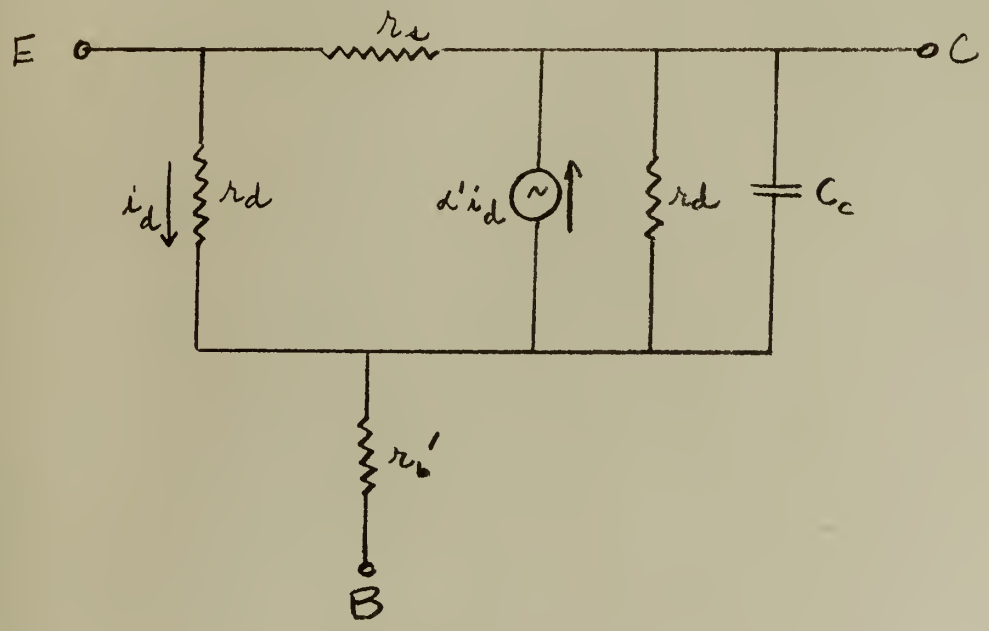


Figure 8

KEIPER'S EQUIVALENT CIRCUIT

If Figure 8 is redrawn using the common emitter connection and the alpha current generator is routed through resistances r_d and r_s, the circuit shown in Figure 9 is obtained.

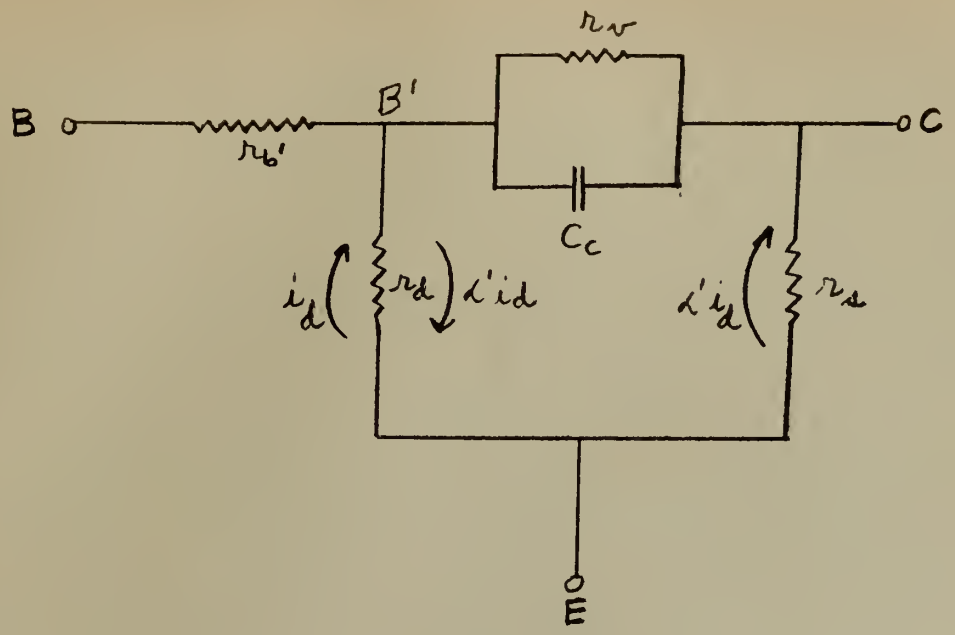
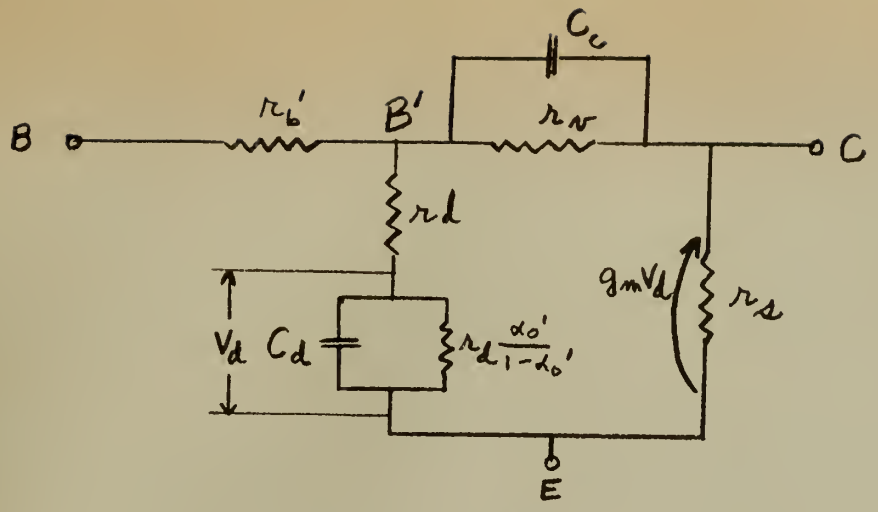


Figure 9

EQUIVALENT CIRCUIT USING COMMON EMITTER CONFIGURATION

If the alpha current generator is represented by a non-frequency dependent current generator and a suitable choice of lumped constants, then the circuit shown in Figure 10 is obtained. Figure 10 is identical to Figure 9 except that the impedance between points B' and E has been replaced by an RC network consisting of r_d , $r_d \frac{\alpha_o'}{1-\alpha_o'}$, and C_d ; also the alpha current generator between points E and C has been given a non-frequency dependent magnitude of $g_m V_d$. The following proof shows that the impedance between points B' and E may be made identical for Figure 9 and Figure 10 with the proper selection of values for the circuit elements shown in Figure 10.



$$g_m = -\frac{1}{r_d}$$

$$C_d = \frac{1}{\omega_c \alpha_o' r_d}$$

Figure 10

EQUIVALENT CIRCUIT WITH THE α GENERATOR REPLACED BY LUMPED CONSTANTS AND A NON-FREQUENCY DEPENDENT CURRENT GENERATOR

For Figure 10

$$Z'_{B'E} = r_d + \frac{r_d \frac{\alpha_o'}{1-\alpha_o'} \left(\frac{1}{j\omega C_d}\right)}{r_d \frac{\alpha_o'}{1-\alpha_o'} + \frac{1}{j\omega C_d}}$$

$$Z'_{B'E} = r_d \left(1 + \frac{\alpha_o'}{j\omega C_d \alpha_o' + 1 - \alpha_o'}\right)$$

$$Z'_{B'E} = r_d \left(\frac{1 + j\omega C_d r_d \alpha_o'}{1 - \alpha_o' + j\omega C_d r_d \alpha_o'}\right)$$

Therefore:

$$Z_{B'E} = Z'_{B'E}$$

if $a = \omega C_d r_d \alpha_o'$

$$C_d = \frac{1}{\omega_c r_d \alpha_o'}$$

For Figure 9

$$Z_{B'E} = \frac{r_d}{1 - \alpha'}$$

$$\alpha' = \frac{\alpha_o'}{1 + ja} \qquad a = \frac{\omega}{\omega_{c\alpha'}}$$

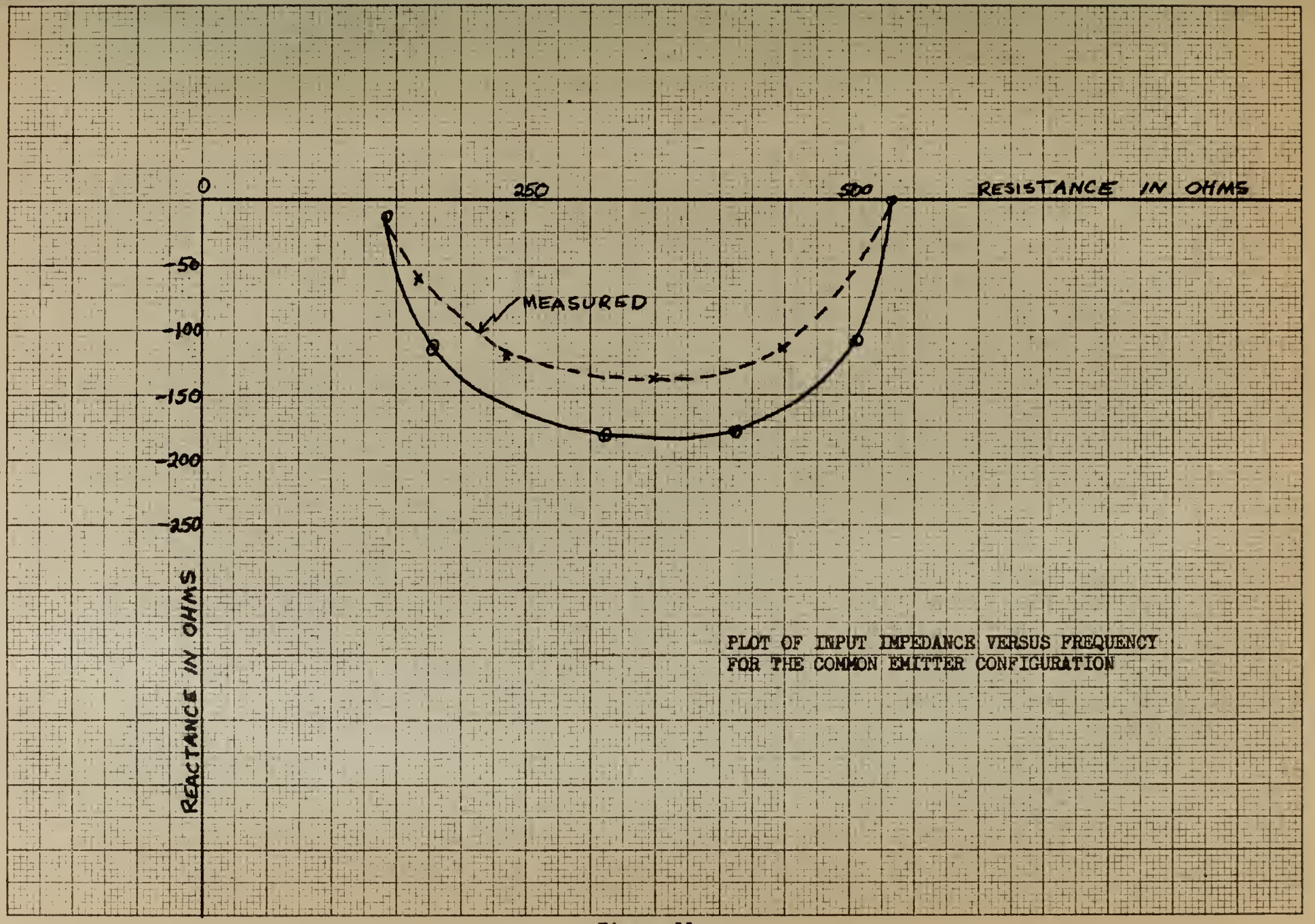
$$Z_{B'E} = r_d \frac{1}{1 - \frac{\alpha_o'}{1+ja}}$$

$$Z_{B'E} = r_d \frac{1+ja}{(1-\alpha_o) + ja}$$

If g_m is made equal to $-\frac{1}{r_d}$, it is immediately apparent that the low frequency short circuit current gain of Figure 10 is equal to that of Figure 9. The variation of magnitude and phase angle of α' with frequency is corrected for by the time constant of C_d and $r_d \frac{\alpha_o'}{1-\alpha_o'}$ in Figure 10.

The circuit of Figure 10 was checked by Philco engineers using a bridge to measure the input impedance versus frequency of a Philco SB 100 transistor with common emitter short-circuited output configuration. The frequencies used were varied from 0 to 50 mc. Figure 11 shows a plot of the theoretically calculated input impedance curve as compared with the experimentally determined curve. The two curves are in good correspondence. The same plot was taken for a common base configuration and showed fairly good correspondence, as shown in Figure 12.

At frequencies exceeding 50 mc, C_{Te} must be taken into account even though it is in parallel with a low resistance, i.e., r_d. This fact was determined experimentally by plotting the input impedance versus frequency with the common emitter short-circuited output configuration of a Philco experimental high frequency transistor. The frequency was varied from 0 to 100 mc. At 100 mc the input impedance was approximately equal to r_b' alone instead of r_b' plus r_d. This indicated that r_d, shown in Figure 10, was shunted out by a capacitance at frequencies approaching 100 mc. The circuit shown in Figure 10 was modified by the author as shown in Figure 13 by placing a capacitance, C, in shunt with all the resistance in the emitter circuit except r_b'. The derivation of values for the circuit elements in Figure 10 is given in Appendix III.



PLOT OF INPUT IMPEDANCE VERSUS FREQUENCY
FOR THE COMMON EMITTER CONFIGURATION

Figure 11

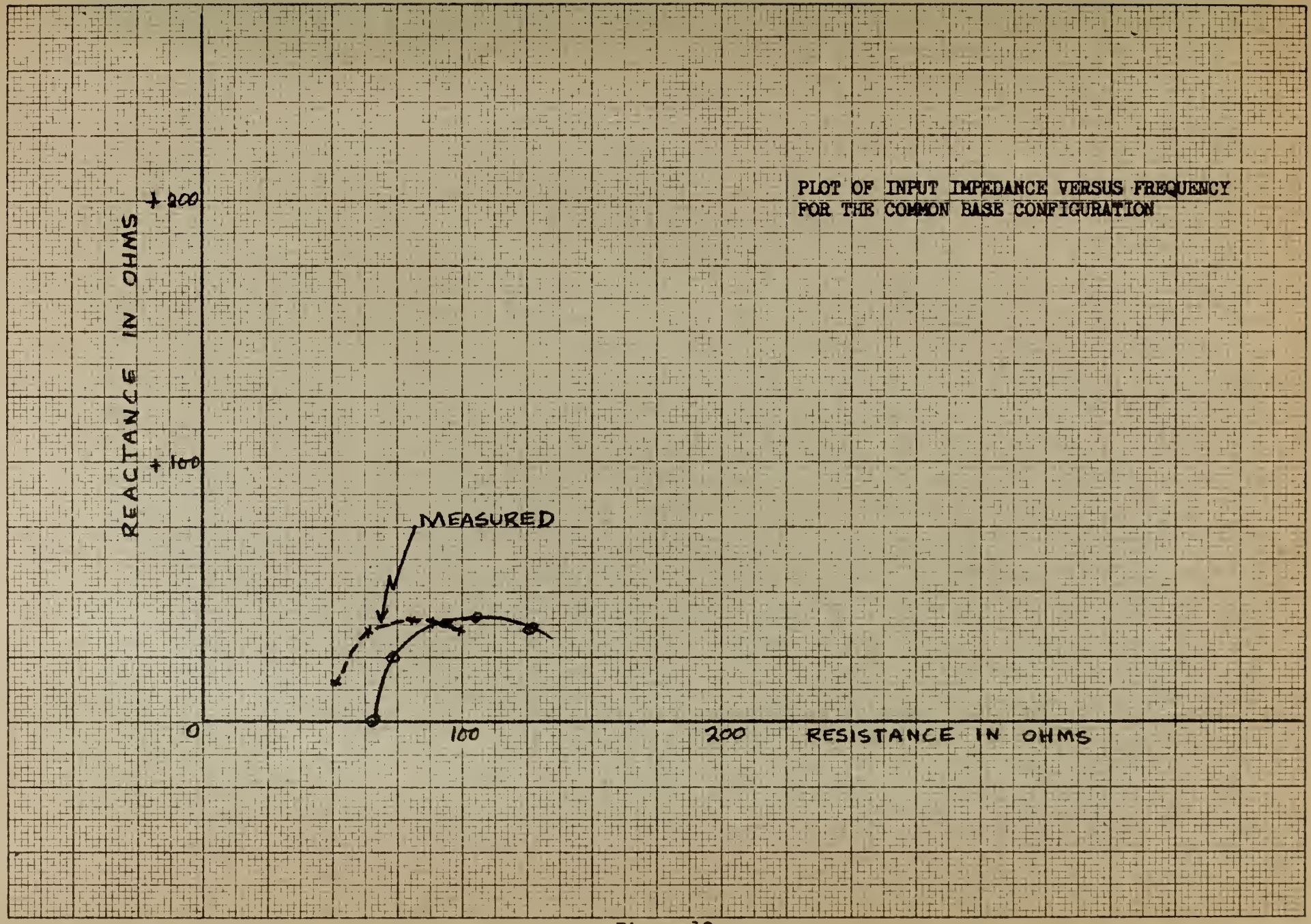

PLOT OF INPUT IMPEDANCE VERSUS FREQUENCY
FOR THE COMMON BASE CONFIGURATION
REACTANCE IN OHMS
+200
+100
0
MEASURED
100
200
RESISTANCE IN OHMS

Figure 12

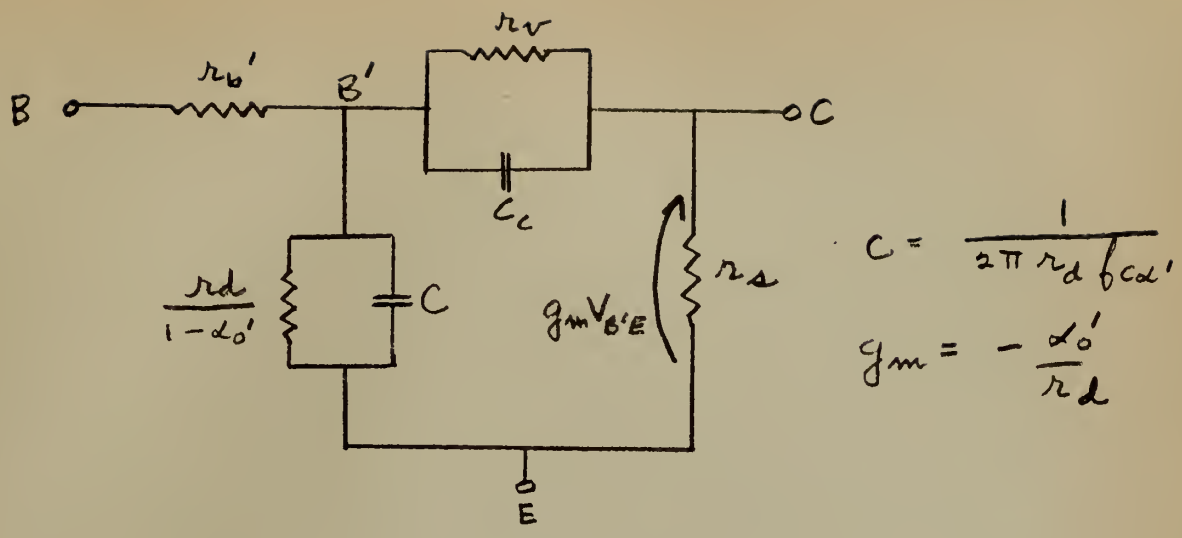


Figure 13

EQUIVALENT CIRCUIT WITH A CAPACITANCE C SHUNTING ALL THE RESISTANCE IN THE EMITTER CIRCUIT EXCEPT r_b'

Figure 14 shows a theoretical and experimental plot of input impedance versus frequency for data taken using the common emitter short-circuited output configuration. The data was taken and plotted by the writer in order to verify the equivalent circuit shown in Figure 13. The plot shows close agreement between experimental and theoretical results. The theoretical values were determined by making use of the circuit shown in Figure 13.

At frequencies above 100 mc, all factors shown in Figure 7 will have to be considered in developing an equivalent circuit. Also such extraneous factors as inter-lead capacitance, shielding can effects, and inductance of all connecting wires will become significant. Therefore, the author believes that any accurate equivalent circuit will be extremely complex at best, and probably impossible to formulate.

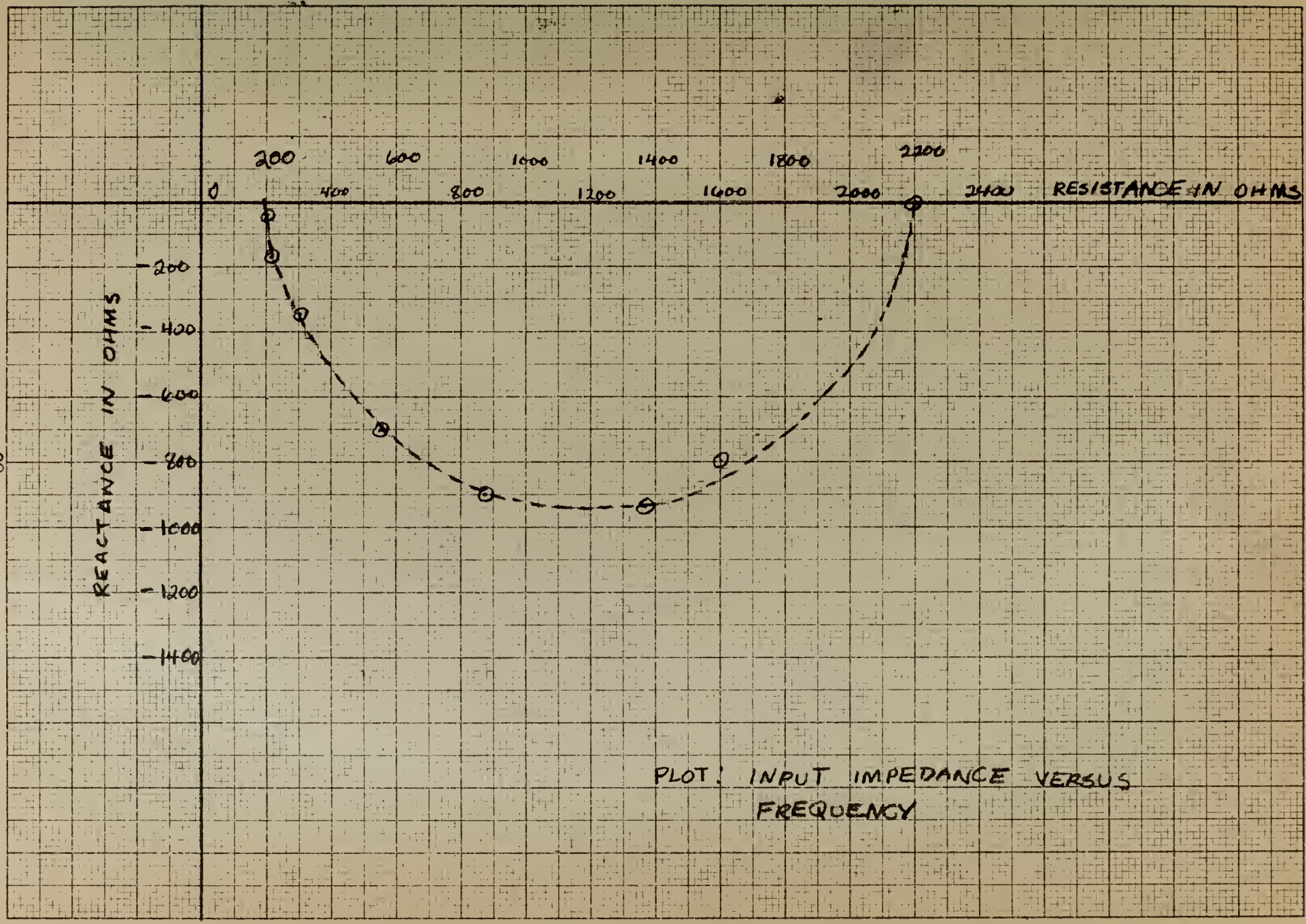

200
600
1000
1400
1800
2200
0
400
800
1200
1600
2000
2400
RESISTANCE IN OHMS
-200
-400
-600
-800
-1000
-1200
-1400
REACTANCE IN OHMS
PLOT: INPUT IMPEDANCE VERSUS FREQUENCY

Figure 14

CHAPTER V

RECENT TRENDS IN HIGH FREQUENCY TRANSISTOR DEVELOPMENT

1. General Discussion

This chapter is devoted mainly to analyzing relatively recent developmental work on high frequency surface barrier transistors. Specifically, the limitations of standard PNP surface barrier transistors are discussed as well as the new types of surface barrier transistors such as the PNIP, graded base, and low α_o surface barrier transistors. The original theory concerning PNIP and graded base transistors was developed for transistor types other than surface barrier transistors. However, the Philco Corporation applied this theory in constructing surface barrier transistors.

2. Limitations of PNP High Frequency Surface Barrier Transistors

Very high frequency surface barrier transistors, such as the Philco L5117 PNP surface barrier transistor, are limited powerwise to about ten milliwatts. This is largely due to the fact the base region is so thin ($.4 \times 10^{-4}$ inches) that the phenomena known as electrical punch-through and voltage breakdown occur at fairly low collector voltages. Electrical punch-through occurs at a collector voltage high enough to extend the collector-base transition region entirely through the base, thereby shorting out the emitter to the collector [12]. Voltage breakdown occurs when the collector voltage is raised high enough to rip electrons directly out of the valence band of the germanium atoms which lie in the transition region. With different transistors either punch-through or voltage breakdown may occur first as the collector voltage is increased. Another power

limitation of high frequency surface barrier transistors is that their relatively small junction areas will heat up comparatively easily if the power output is increased above ten milliwatts. If the junction temperature exceeds 70 degrees centigrade, then the low temperature characteristics of a germanium transistor no longer are valid, and temperature runaway may occur. (Silicon transistors maintain their low temperature characteristics up to a junction temperature of 150 degrees centigrade.)

3. PNIP Transistors, Using the Surface Barrier Technique of Construction

PNIP transistors have been developed to increase the frequency response as well as the power and voltage rating of PNP transistors [2]. This is accomplished by sandwiching a region of high resistivity n-type germanium between the base and the collector.

The collector-base transition region, with PNIP construction extends entirely across the intrinsic region and slightly into the base and collector regions. The addition of an intrinsic region gives a PNIP surface barrier transistor the following advantages over a PNP surface barrier transistor:

1) The collector voltage may be increased to 40 to 100 volts without fear of collector-base voltage breakdown or electrical punch-through, since the field strength per volt is decreased.

2) The cross sectional area of the collector-base junction may be increased. This is possible because the value of C_c is made very small by the insertion of the intrinsic layer. The value of C_c varies between 0.1 and 2.0 $\mu\mu f$.

3) The collector-base junction temperature will be lower because of the increased surface area from which heat may radiate.

4) The value of base resistivity may be reduced without fear of collector-base voltage breakdown. Lowering the value of base resistivity is advantageous in that it will reduce the magnitude of r_b' and speed the diffusion of minority carriers across the base region. Disadvantages of reducing r_b' include a reduction in emitter efficiency, an increase in recombination rate of minority and majority charge carriers, and an increase in the value of emitter-base transition capacity.

The relative amount of time spent by the minority carriers in drifting through the intrinsic layer as compared to diffusing through the base region depends on the widths of the two regions. However, the two times are usually comparable to one another since the intrinsic region is several times as thick as the base region. Computation showing approximate drift and diffusion time through a PNIP surface barrier transistor is given below.

1) Diffusion time in seconds $- t_d$ [2]

$$t_d = \frac{W^2}{2D_p}$$

$$t_d = \frac{(10^{-4})^2}{2(19)} = .25 \times 10^{-9} \text{ secs}$$

2) Drift time in seconds $- t_{dr}$

$$t_{dr} = \frac{t}{5(10^6)}$$

$$t_{dr} = \frac{5(10^{-4})}{5(10^6)} = 10^{-10} \text{ secs}$$

where t equals the depletion layer thickness in cms.

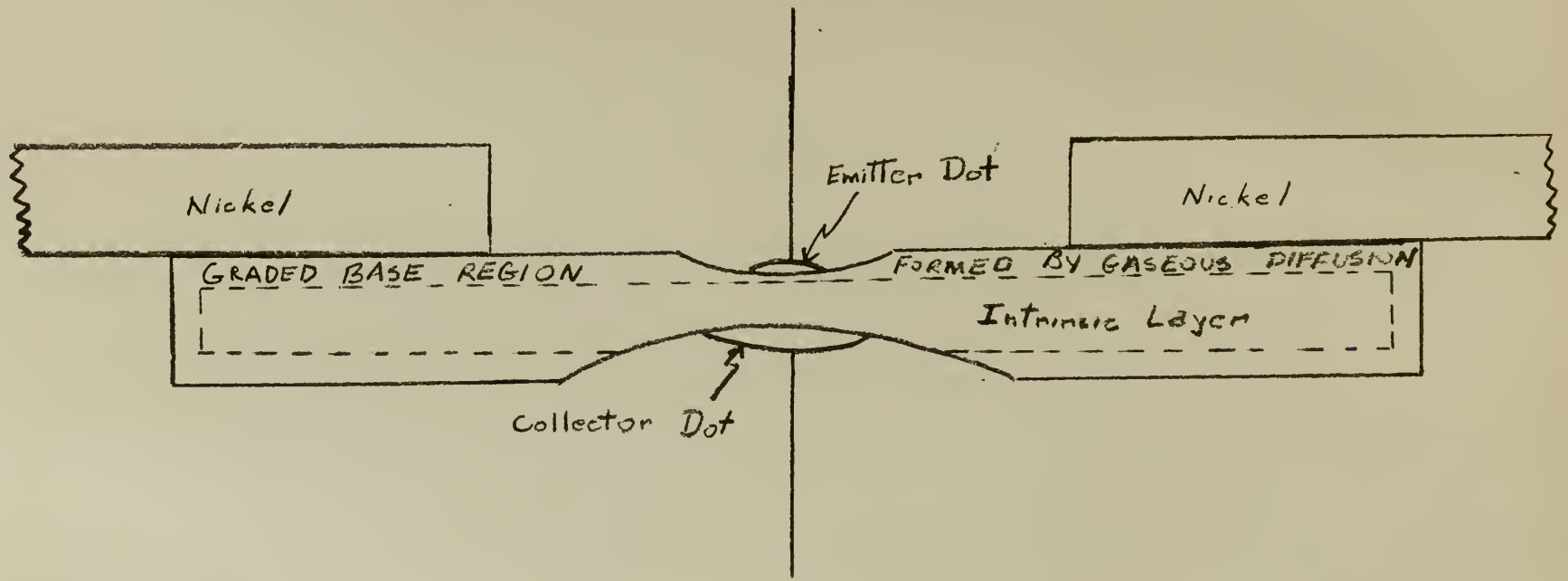
Drift time will reduce the frequency response of the basic α' generator [13]. Therefore, if the α' generator was the basic frequency limiting factor in determining the high frequency cut-off of α , the

intrinsic layer would impair the high frequency response of a surface barrier PNP transistor. However, since $f_{c\alpha'}$ for a PNP surface barrier transistor is about 2940 mc, a reduction of $f_{c\alpha'}$ by a factor of one-half in the PNIP type still gives a frequency response of 1470 mc. Thus, it is obvious that the intrinsic layer will permit an increased power rating of a high frequency surface barrier transistor without a reduction of the frequency response. If the collector-time constant circuitry involving C_c and r_b' was limiting the frequency response of the α generator then the intrinsic layer would, by its very existence, reduce C_c, and thus increase the high frequency surface barrier transistor response.

The previously derived equivalent circuit shown in Figure 13 for a PNP surface barrier transistor applies equally well to a PNIP surface barrier transistor. However, the values of the circuit components valid for a PNIP surface barrier transistor must be used in the equivalent circuit [2].

4. Graded Base Transistor, Using the Surface Barrier Technique of Construction

A cross section of a graded base PNIP surface barrier transistor is shown in Figure 15. The graded base transistor is constructed by diffusing phosphorous vapor into a cake of intrinsic germanium. Then the standard surface barrier technique of electrolytic etching is used before electroplating the emitter and collector dots. This method of construction will give an exponential distribution of n-type impurity in the base region as shown in Figure 16 [13].



GRADED BASE PNIP TRANSISTOR,
USING THE SURFACE BARRIER TECHNIQUE OF CONSTRUCTION

Figure 15

Figure 16

CONDUCTIVITY DIAGRAM

As a result of the exponential distribution of n-type impurity in the base region, a linear drift field will be set up in the base region [13]. This drift field will cause holes to flow under the influence of an electric field, as well as diffuse through the base region. Hence, the time of transit through the base region is reduced, and the frequency response of the transport factor β is enhanced. C. A. Lee, of Bell Laboratories, points out that the frequency enhancement of β due to built-in fields is at most a factor of two [13].

A graded base PNP surface barrier transistor is constructed similarly to a PNIP surface barrier transistor except that the electrolytic etching process at the collector is extended until the intrinsic region is completely penetrated before electroplating the collector dot. A cross section of a graded base PNP surface barrier transistor is shown in Figure 17.

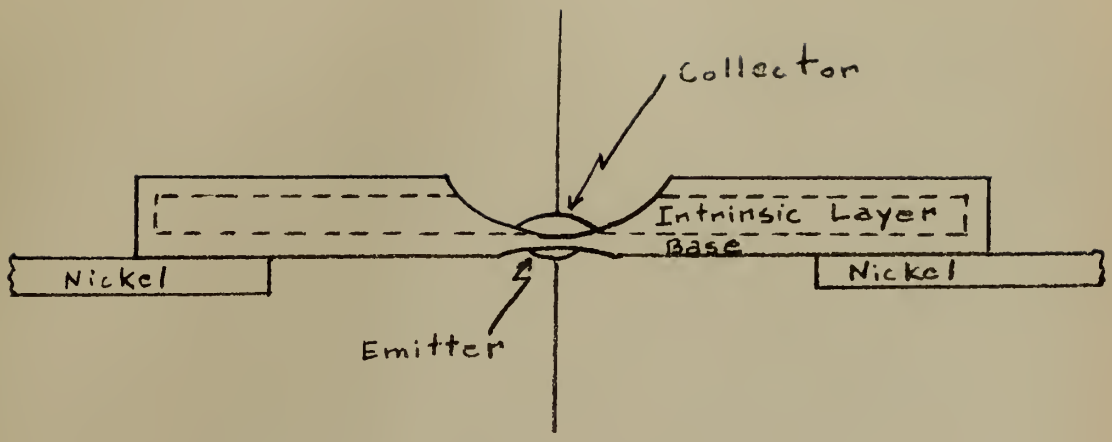


Figure 17

PNP GRADED BASE TRANSISTOR,
USING THE SURFACE BARRIER TECHNIQUE OF CONSTRUCTION

Graded base construction will enhance the frequency response of a surface barrier transistor providing the transport factor β is the frequency limiting factor in the transistor. Previous calculations show that the cut-off frequency due to β is 2940 mc with VHF experimental PNP surface barrier transistors. Therefore, PNIP type construction should not alter the frequency response of the PNP surface barrier transistor which is limited by the time constant of the emitter circuitry to a value of 140 mc. This is borne out experimentally by the fact that the PNP surface barrier transistors tested by engineers at the Philco Corporation both with and without graded base construction have comparable cut-off frequencies.

4. Low Alpha Zero Transistors Using the Surface Barrier Technique of Construction

All material previously discussed relates to surface barrier transistors with $\alpha_o > 0.9$. Surface barrier transistors having $\alpha_o < 0.9$ will now be analyzed. This work was done by the author in conjunction with engineers from the Philco Corporation. Philco does not attempt to manufacture low α_o transistors. However, in the process of making high α_o transistors, a low α_o transistor will occasionally be produced. The high frequency response properties of a low α_o transistor are different from those of a high α_o transistor.

Transistors known to have a low α_o from previous measurements were tested by measuring their value of input impedance versus frequency. The circuit for this experiment was the common emitter short-circuited output configuration (hereafter referred to as Experiment A). When the values of input impedance determined in Experiment A were plotted as reactance versus resistance, the plots resulted in a curve shaped like the arc of a circle whose total arc length was less than 180 degrees. The lower the value of α_o for the transistor, the less was the number of degrees of the arc length. When the value of α_o equalled 0.5 the data obtained, by performing Experiment A, plotted as a pure resistance. When the value of α_o was less than 0.5 the plot became inductive, as opposed to being capacitive for a value of α_o greater than 0.5. The phenomenon just described is roughly sketched in Figure 18.

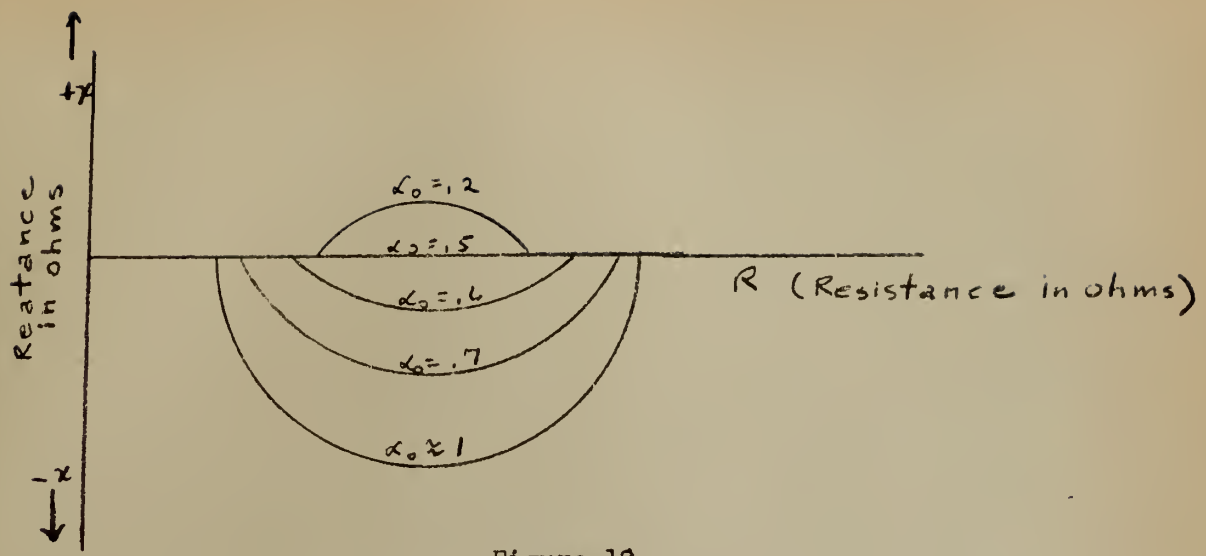


Figure 18

FAMILY OF LOW α_0 CURVES

An equivalent circuit for a low α_0 surface barrier transistor is shown in Figure 19. The configuration of the equivalent circuit is identical to that for high α_0 equivalent circuits, except that the expression for α must be modified.

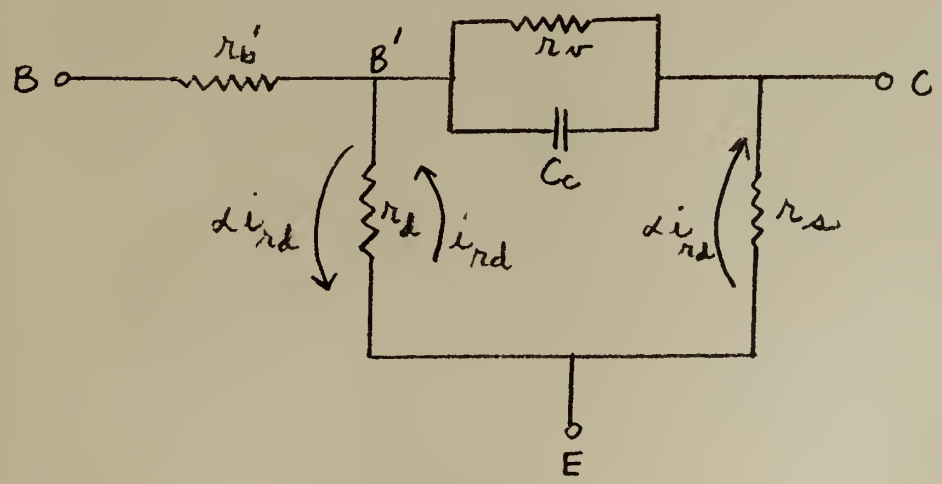


Figure 19

EQUIVALENT CIRCUIT FOR A LOW α_0 TRANSISTOR

The effective impedance between points B' and E, in Figure 19, is $\frac{r_d}{1-\alpha}$. This may be understood if one considers that the effective impedance of r_d must be raised above its nominal value since the αi_{rd} current generator will reduce the total effective current flowing through r_d to $i_{rd} - \alpha i_{rd}$. The total input impedance of the equivalent circuit shown in Figure 19 when Experiment A is performed is H_{11e}. If the reactance of C_c and the resistance of r_v are very large, then the impedance of the branch of the equivalent circuit between B' and C may be considered as an open circuit as compared with the impedance $\frac{r_d}{1-\alpha}$. Therefore, the input impedance of the circuit shown in Figure 19 reduces to

$$H_{11e} \approx r_{b'} + \left(\frac{1}{1-\alpha}\right) r_d$$

The only frequency dependent term in the expression given for H_{11e} is α. If the standard expression for α is assumed, i.e.,

$$\alpha = \frac{\alpha_o}{1 + j\alpha}$$

then, using the same procedure as shown on Pages 22, 23, and 24, Figure 19 may be altered to give the equivalent circuit shown in Figure 20.

A plot of input impedance, with frequency as a parameter, for the equivalent circuit shown in Figure 20 will always give a semi-circle as shown by the $\alpha_o \approx 1$ curve in Figure 18. The semi-circle is produced by the effect of the parallel combination of C_1 and R_1 in Figure 20. However, it has been determined experimentally that the input impedance of low α_o transistors varies differently with frequency than does that of a high α_o transistor. This phenomenon is illustrated in Figure 18.

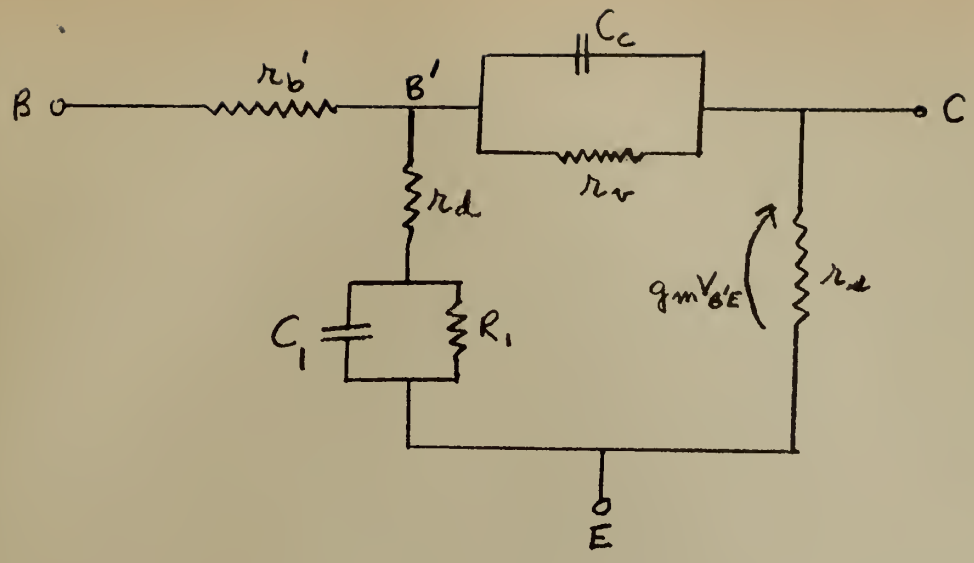


Figure 20

EQUIVALENT CIRCUIT WITH THE ALPHA GENERATOR REPLACED BY LUMPED CONSTANTS AND A CURRENT GENERATOR

Consequently, it is believed that the expression for α , where

$$\alpha = \frac{\alpha_o}{1 + j a}$$

and

$$a = \frac{b}{b c \alpha'}$$

is not valid for low α_o transistors, and a new expression for α and $\frac{1}{1-\alpha}$ will be derived. This new expression will treat both the emission efficiency, γ , and the transport factor, β , as frequency dependent. A mathematical development follows.

Let

$$\alpha = \beta\gamma$$

Assume $\beta_o \approx 1$

$$\gamma_o = \frac{I_{hco}}{I_{hco} + I_{eco}}$$

$$\gamma_o = \frac{1}{1 + \frac{I_{eco}}{I_{hco}}}$$

$$\frac{I_{eco}}{I_{hco}} = \frac{1 - \alpha_o}{\alpha_o}$$

Where: I_{hco} = Low frequency value of hole current injected into the base region at the emitter-base junction.

I_{eco} = Low frequency value of the electron current flowing through the emitter-base junction.

If a frequency dependence is given to $\frac{I_{ee}}{I_{he}}$, then

$$\frac{I_{ee}}{I_{he}} = \frac{1 - \alpha_o}{\alpha_o}(1 - jb)$$

but $$\gamma = \frac{1}{1 + \frac{I_{ee}}{I_{he}}}$$

If the frequency effect of β assumes its standard form of $\frac{1}{1+ja}$, then

$$\alpha = \beta\gamma$$

$$\alpha = \left(\frac{1}{1+ja}\right) \frac{1}{1 + \frac{1-\alpha_o}{\alpha_o}(1 - jb)}$$

Let $\frac{\alpha_o}{1-\alpha_o} = H$

Substituting $\alpha = \left(\frac{1}{1+ja}\right)\left(\frac{1}{1+\frac{1}{H}(1-jb}\right)$

$$\alpha = \frac{1}{(1+ja)\left[(1+\frac{1}{H}) - j\frac{b}{H}\right]}$$

$$\alpha = \frac{1}{(1+\frac{1}{H}+\frac{ba}{H}) + j\left[a(1+\frac{1}{H}) - \frac{b}{H}\right]}$$

$$\alpha = \frac{\left[1+\frac{1}{H}+\frac{ba}{H}\right] - j\left[a(1+\frac{1}{H}) - \frac{b}{H}\right]}{(1+\frac{1}{H}+\frac{ba}{H})^2 + \left[a(1+\frac{1}{H}) - \frac{b}{H}\right]^2}$$

But $H_{11c} = rb' + \frac{r\alpha}{1-\alpha}$

If for $\alpha_o = .5$ the expression is real, then

$$a(1+\frac{1}{H}) - \frac{b}{H} = 0 \qquad H = \frac{\alpha_o}{1-\alpha_o} = \frac{.5}{.5} = 1$$

Then $2a - b = 0$

$b = 2a$

Substituting $b = 2a$

$$\alpha = \frac{1}{(1+ja)\left[\frac{H+1}{H} - j\frac{2a}{H}\right]}$$

$$\alpha = \frac{1}{(1+ja)\left[\frac{1}{\alpha_o} - j\frac{2a(1-\alpha_o)}{\alpha_o}\right]}$$

$$\frac{1}{1-\alpha} = \frac{(1+ja)(1-j2a(1-\alpha_0))}{(1+ja)(1-j2a(1-\alpha_0)) - \alpha_0}$$

$$\frac{1}{1-\alpha} = \frac{1+2a^2(1-\alpha_0)+ja(2\alpha_0-1)}{1-\alpha_0+2a^2(1-\alpha_0)+j(2\alpha_0-1)a}$$

$$\frac{1}{1-\alpha} = 1 + \frac{\alpha_0}{1-\alpha_0+2a^2(1-\alpha_0)+j(2\alpha_0-1)a}$$

$$\frac{1}{1-\alpha} = 1 + \alpha_0\left[\frac{1-\alpha_0+2a^2(1-\alpha_0)-j(2\alpha_0-1)a}{[1-\alpha_0+2a^2(1-\alpha_0)]^2+(2\alpha_0-1)^2a^2}\right]$$

D.C. check

$$\frac{1}{1-\alpha} = \frac{1}{1-\alpha_0}$$

Frequency = ∞ check

$$\frac{1}{1-\alpha} = 1$$

Plots of the theoretical formula developed for $\frac{1}{1-\alpha}$ are shown in Figures 21 through 23. Experimental plots obtained by plotting data obtained from Experiment A are shown in Figures 24 through 26. While the experimental curves do not exactly match the theoretical curves, their shape is quite similar.

Any equivalent circuit components computed for Figure 20 using the derived theoretical formulas for α and $\frac{1}{1-\alpha}$ would have values that would be complex frequency dependent functions. However, the functions would be so complicated as to be of questionable practical value.

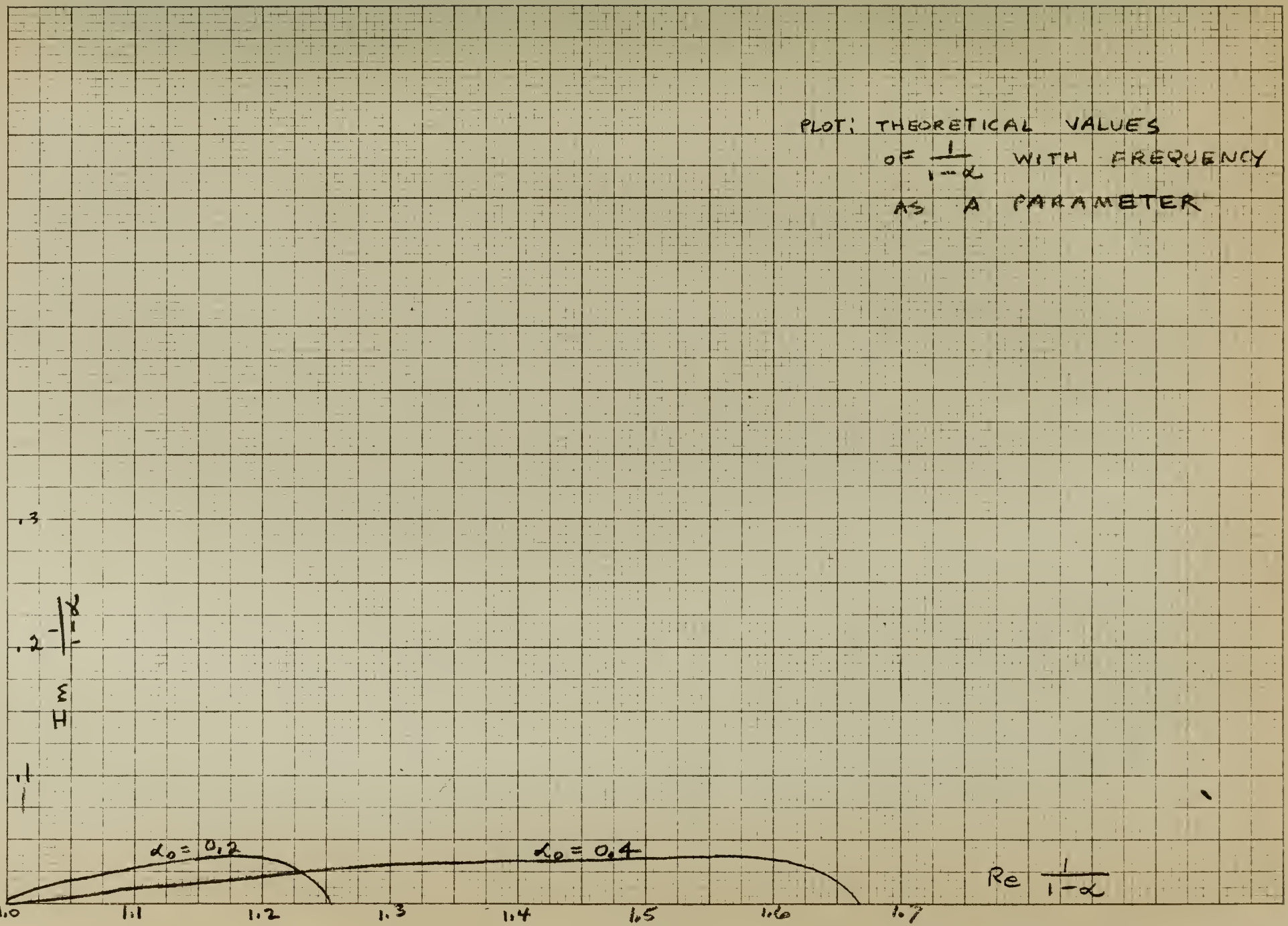

PLOT; THEORETICAL VALUES
OF $\frac{1}{1-\alpha}$ WITH FREQUENCY
AS A PARAMETER
45
.3
.2
$\left|\frac{1}{1-\alpha}\right|$
$\alpha_0 = 0.2$
$\alpha_0 = 0.4$
1.0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
Re $\frac{1}{1-\alpha}$

Figure 21

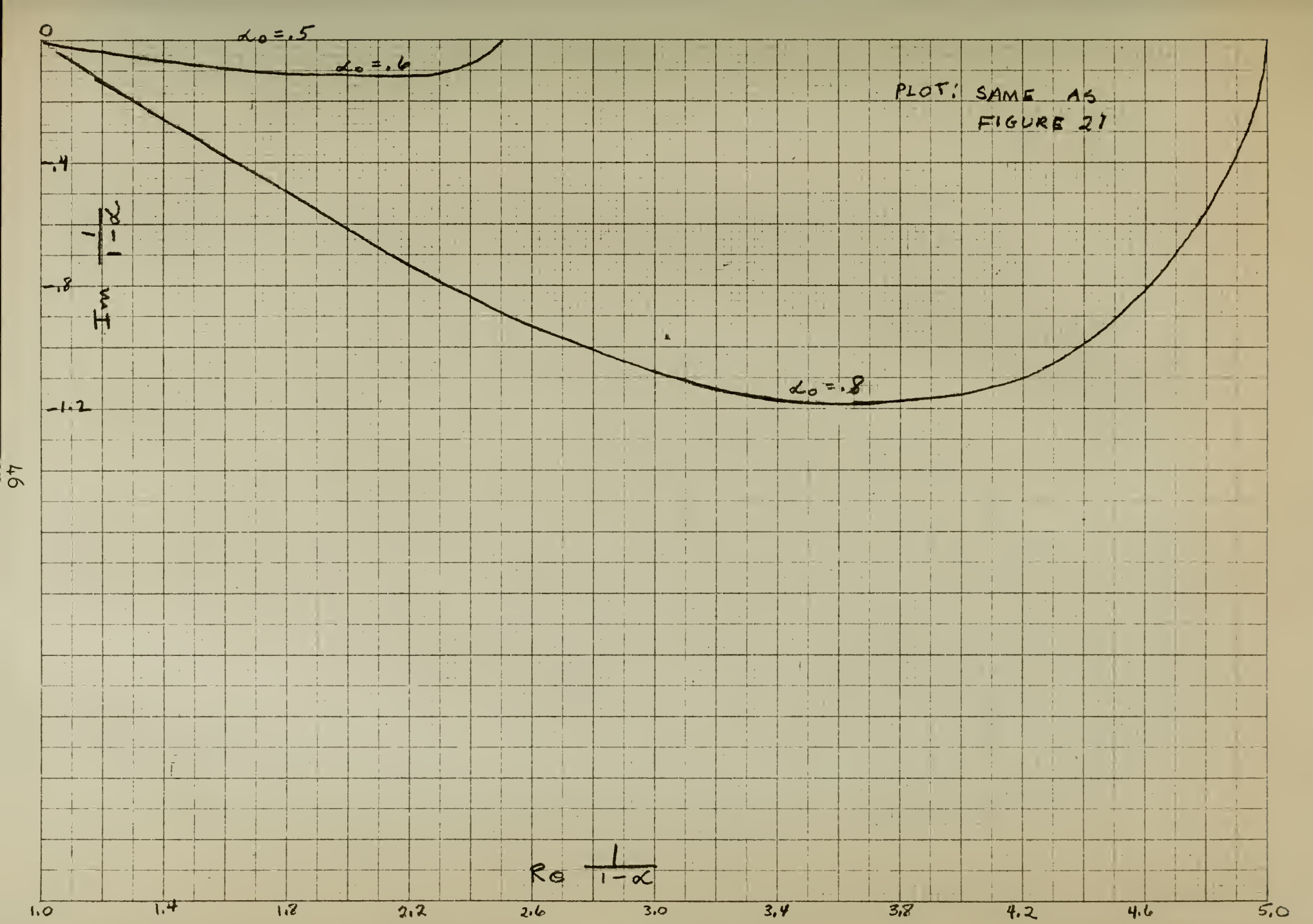

0
$\alpha_0 = .5$
$\alpha_0 = .6$
$\alpha_0 = .8$
PLOT: SAME AS FIGURE 21
-.4
-.8
-1.2
$\ln \frac{1}{1-\alpha}$
$R_\Theta \frac{1}{1-\alpha}$
1.0
1.4
1.8
2.2
2.6
3.0
3.4
3.8
4.2
4.6
5.0

Figure 22

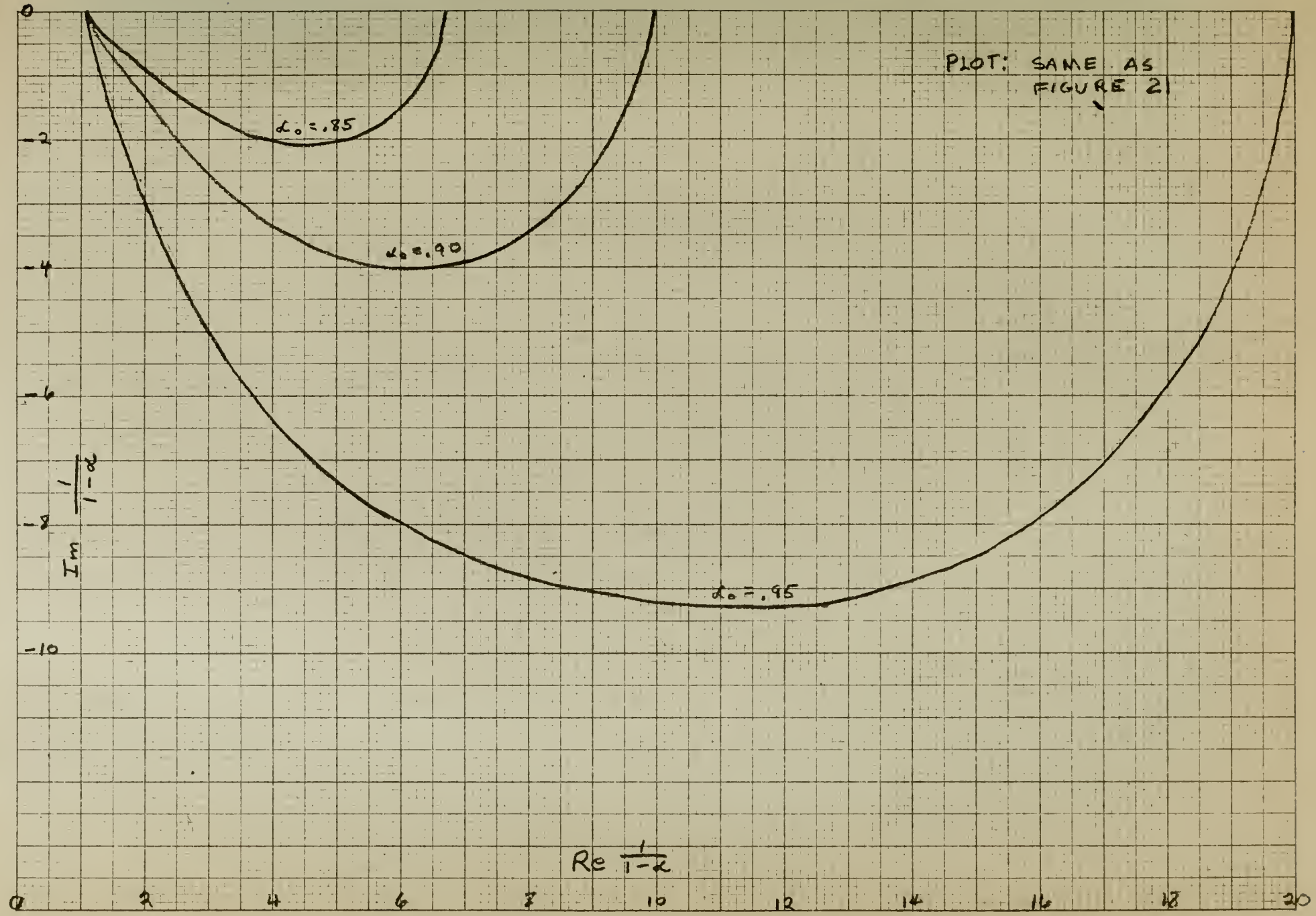

PLOT: SAME AS FIGURE 2
$\alpha_0 = .85$
$\alpha_0 = .90$
$\alpha_0 = .95$
$\mathrm{Im}\ \frac{1}{1-\alpha}$
$\mathrm{Re}\ \frac{1}{1-\alpha}$
0
-2
-4
-6
-8
-10
2
4
6
8
10
12
14
16
18
20

Figure 23

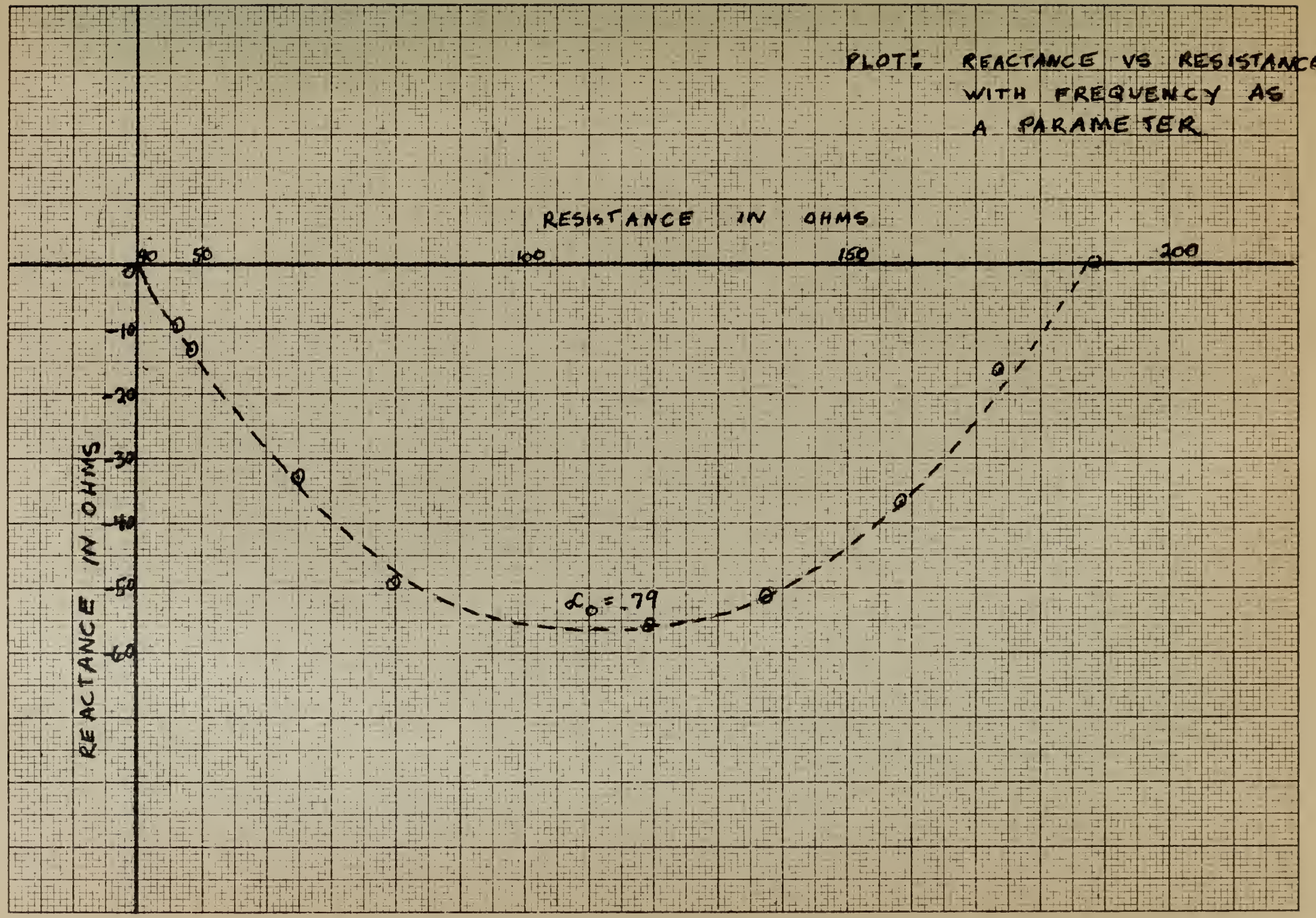

PLOT: REACTANCE VS RESISTANCE WITH FREQUENCY AS A PARAMETER
RESISTANCE IN OHMS
0
50
100
150
200
REACTANCE IN OHMS
-10
-20
-30
-40
-50
-60
$\alpha_0 = .79$

Figure 24

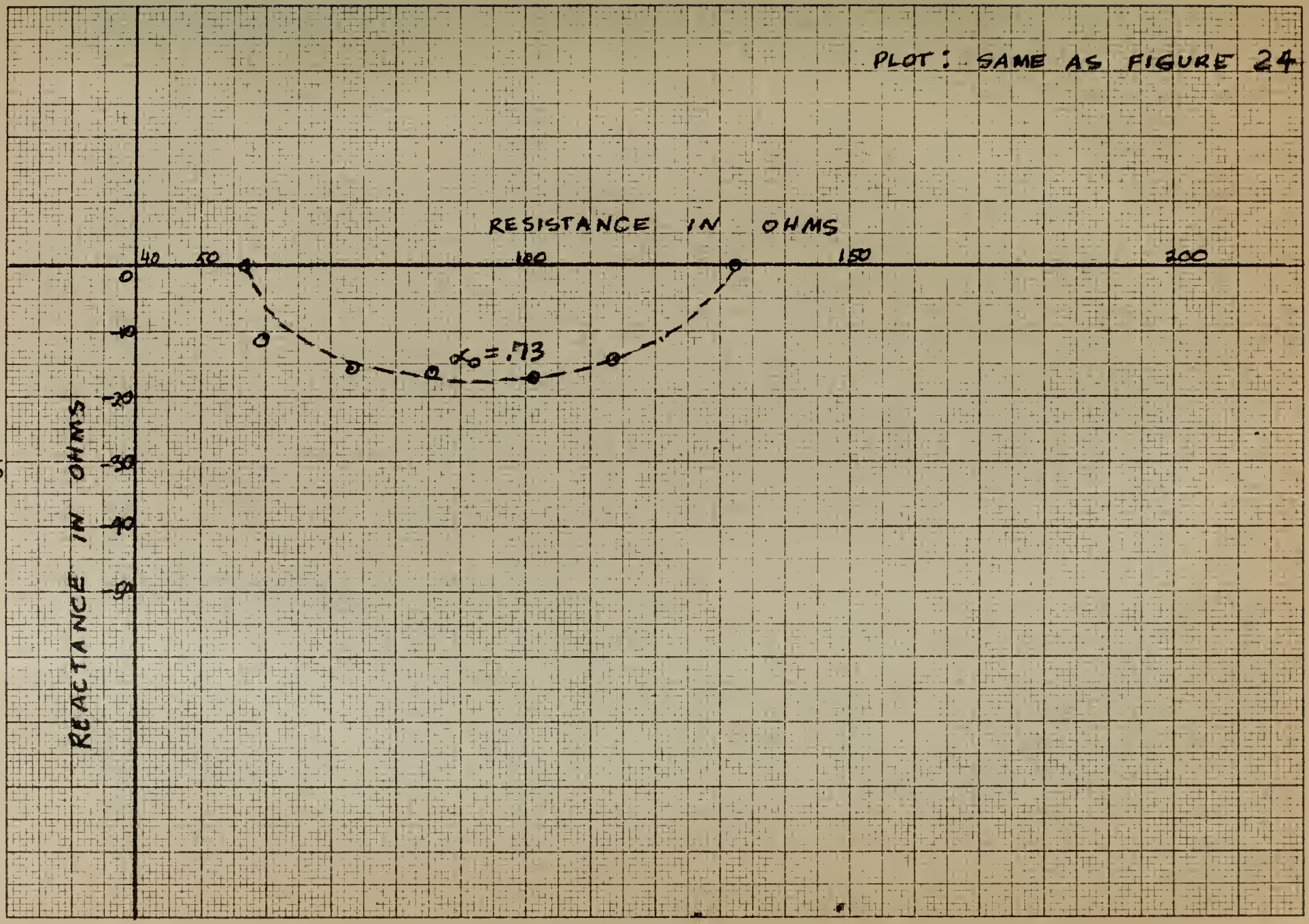

PLOT: SAME AS FIGURE 24
RESISTANCE IN OHMS
40
50
100
150
200
0
-10
-20
-30
-40
-50
REACTANCE IN OHMS
$\alpha_0 = .73$

Figure 25

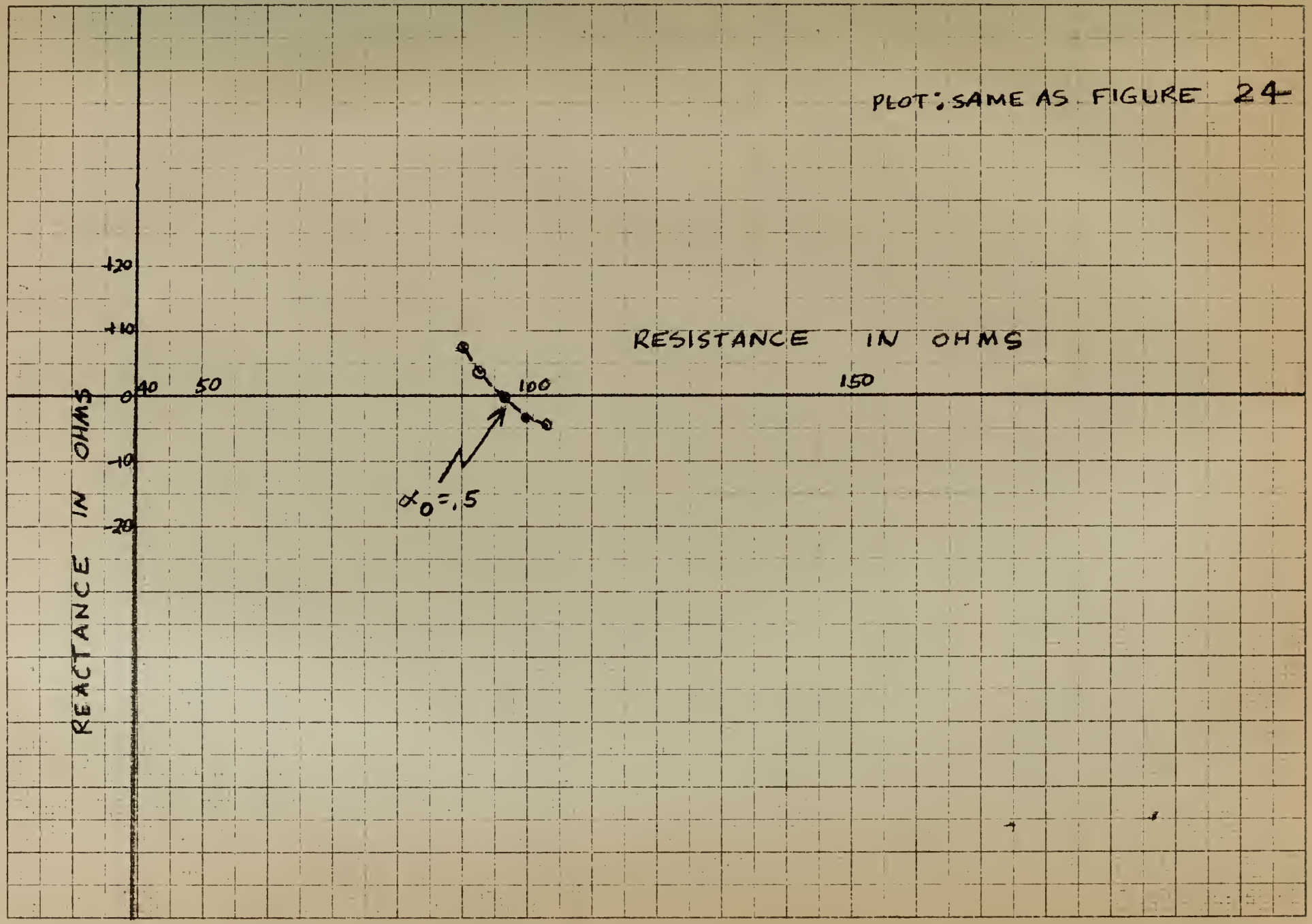

PLOT: SAME AS FIGURE 24
RESISTANCE IN OHMS
REACTANCE IN OHMS
+20
+10
0
-10
-20
40
50
100
150
$\alpha_0 = .5$

Figure 26

CHAPTER VI

CONCLUSIONS

The author has described the various factors of a Philco surface barrier transistor which affect its frequency response. Next, the transistor was considered separated, for analytical purposes, into three sections. The three sections were as follows:

1) The emitter time constant circuitry
2) The intrinsic α' generator
3) The collector time constant circuitry

Each of the three sections was studied to determine its effect on the high frequency response of surface barrier transistors. This study indicated that the emitter time constant circuitry composed of C_{Te} and r_d had the lowest cut-off frequency, (140 mc). Thus, the emitter circuitry appears to be the section of surface barrier transistors which limits their high frequency response.

PNIP and graded base transistors were discussed, and it was pointed out that neither PNIP nor graded base transistors improved the high frequency response of surface barrier PNP transistors because they did not reduce the emitter circuitry time-constant.

The frequency effects of low alpha zero transistors were studied, and while they were novel, low alpha zero transistors did not have a higher frequency response than normal high alpha zero transistors.

The author believes the next logical step to be taken to increase the high frequency response of a surface barrier transistor is to reduce the value of the emitter circuitry time constant. This may be done by any one of the following methods:

1) Reducing the emitter-base junction area in order to reduce C_{T_e}

2) Increasing the base resistivity in order to reduce C_{T_e}

3) Sandwiching an intrinsic layer of germanium between the emitter and base junctions in order to reduce C_{T_e}

4) Operating the transistor at higher emitter currents, if possible, in order to reduce r_d. $\left(r_d = \frac{27}{I_e}\right)$

Of the first three methods suggested for reducing the emitter circuitry time constant, methods two and three are the most feasible from a construction viewpoint. The use of method one would be difficult because the diameter of the emitter dot has already been reduced to about 1.4 mils, and any further reduction will require improved apparatus over that presently used. The fourth method suggested is of limited value in that the power capabilities of the transistor may be exceeded with higher emitter currents.

BIBLIOGRAPHY

1. Early, J. M. — DESIGN THEORY OF JUNCTION TRANSISTORS, Bell System Technical Journal, Vol. XXXII, No. 6, pp 1271-1312, November 1953

2. Early, J. M. — PNIP AND NPIN JUNCTION TRANSISTOR TRIODES, Bell System Technical Journal, Vol. XXXIII, No. 3, pp 517-534, May 1954

3. Early, J. M. — EFFECTS OF SPACE-CHARGE LAYER WIDENING IN JUNCTION TRANSISTORS, Proc. I.R.E., Vol. 40, No. 11, pp 1401-1406, November 1952

4. Steele, E. L. — THEORY OF ALPHA FOR P-N-P DIFFUSED JUNCTION TRANSISTORS, Proc. I.R.E., Vol. 40, No. 11, pp 1424-1428, November 1952

5. Pritchard, R. L. — FREQUENCY VARIATIONS OF CURRENT-AMPLIFICATION FACTOR FOR JUNCTION TRANSISTORS, Proc. I.R.E., Vol. 40, No. 11, pp 1476-1480, November 1952

6. Pritchard, R. L. — FREQUENCY VARIATIONS OF JUNCTION-TRANSISTOR PARAMETERS, Proc. I.R.E., Vol. 42, No. 5, pp 786-799, May 1954

7. Webster, W. M. — ON THE VARIATION OF JUNCTION-TRANSISTOR CURRENT-AMPLIFICATION FACTOR WITH EMITTER CURRENT, Proc. I.R.E., Vol. 42, No. 5, pp 914-920, June 1954

8. Lo, Endres, Zawels, Waldhauer, Cheng — TRANSISTOR ELECTRONICS, Prentice-Hall, 1955

9. Shockley, W. — THE THEORY OF p-n JUNCTIONS IN SEMICONDUCTORS AND p-n JUNCTION TRANSISTORS, Bell System Technical Journal, pp 25-80, July 1949

10. Philco Bulletin — H-1149A-4, p 24

11. Moll, J. L. and Ross, I. M. — TRANSISTOR BASE LAYER RESISTIVITY, Proc. I.R.E., Vol. 44, No. 1, pp 72-78, January 1956

12. Moll, J. L. — JUNCTION TRANSISTOR ELECTRONICS, Proc. I.R.E., Vol. 43, No. 12, pp 1807-1819, December 1955

13. Lee, C. A. — A HIGH-FREQUENCY DIFFUSED BASE GERMANIUM TRANSISTOR, Bell System Technical Journal, Vol. XXXV, No. 1, pp 23-34, January 1956

14. Philco Research Staff — THE SURFACE-BARRIER TRANSISTOR, Proc. I.R.E. Vol. 41, No. 12, pp 1702-1720, December 1953

15. Giacoletto, L. J. — HIGH FREQUENCY JUNCTION TRANSISTORS R.C.A. Review, Vol. XVI, No. 1, pp 34-42, January 1955

16. Zawels, J. — THE NATURAL EQUIVALENT CIRCUIT OF JUNCTION TRANSISTORS, R.C.A. Review, Vol. XVI, No. 3, pp 360-378, September 1955

17. Giacoletto, L. J. — STUDY OF P-N-P ALLOY JUNCTION TRANSISTOR FROM D-C THROUGH MEDIUM FREQUENCIES R.C.A. Review, Vol. XV, No. 4, pp 506-562, December 1954

18. Mueller, C. W. and Pankove, J. I. — A P-N-P TRIODE ALLOY JUNCTION TRANSISTOR FOR RADIO-FREQUENCY AMPLIFICATION, R.C.A. Review, Vol. XIV, No. 4, pp 586-598, December 1953

APPENDIX I

FREQUENCY DEPENDENCE OF γ

Emission efficiency, γ, for high α_o transistors has been considered non-frequency dependent in this thesis. This has been possible because C_{Te} has been treated as part of the emitter time constant circuitry instead of as a factor affecting the emission efficiency.

R. L. Pritchard gives an approximate expression for γ [67] which considers γ frequency dependent. If approximations are made which are possible with a VHF experimental Philco transistor, the following explanation can be given to justify considering γ non-frequency dependent, even when using the formula given by Pritchard.

$$\gamma = \left\{1 + \left[A\,(1+j\omega\tau_e)^{1/2} + (j\omega C_e' r_e'/\gamma_o)\right]\left[\tanh(j\omega\tau_b)^{1/2}/(j\omega\tau_b)^{1/2}\right]\right\}^{-1}$$

Where:

$$A = \frac{1-\gamma_o}{\gamma_o}$$

$C_e' = C_{Te} =$ Emitter-base transistion capacity.

$$r_e' = r_d = \frac{27}{I_e\ (ma)}$$

Since $\gamma_o \approx 1$ and τ_e is made very short by highly doping the emitter, the term $A(1+j\omega\tau_e)^{1/2} \approx 0$. The hyperbolic term $\tanh(j\omega\tau_b)^{1/2}/(j\omega\tau_b)^{1/2}$ remains constant with

frequency, providing the frequency is low compared to $f_{c\alpha'}$. Since $f_{c\alpha'}$ is in the order of 2940 mc, the hyperbolic term may be considered constant at frequencies in the 0 to 300 mc range.

Thus the only term remaining frequency dependent in the expression for γ is $j\omega C_{\epsilon}' r_{\epsilon}' / \gamma_o$. This term accounts for the emitter-base transition capacity and the emitter resistance. Since these two terms have been accounted for in the emitter circuitry time constant discussed in this thesis, no basic discrepancy exists between the above expression for γ and the basic alpha generator development in this thesis.

APPENDIX II

EMITTER-BASE TRANSITION CAPACITY

Many authors consider C_{Te} a negligible parameter as compared to diffusion capacity when considering high frequency effects in transistors [17,18]. Others say it is large and therefore must be taken into account at high frequencies [8,6].

Theory has been developed in this thesis for the alpha generator assuming a value of C_{Te} in the order of 30 to 50 $\mu\mu f$. Also, the author has treated the effect of diffusion capacitance lightly. This has been possible with very high frequency experimental Philco transistors because of the following reasons:

1) The base resistivity is very low.

$$\rho_B \approx .01 \text{ ohm-cms}$$

2) The emitter resistivity is extremely low.

$$\rho_e \approx .001 \text{ ohm-cms}$$

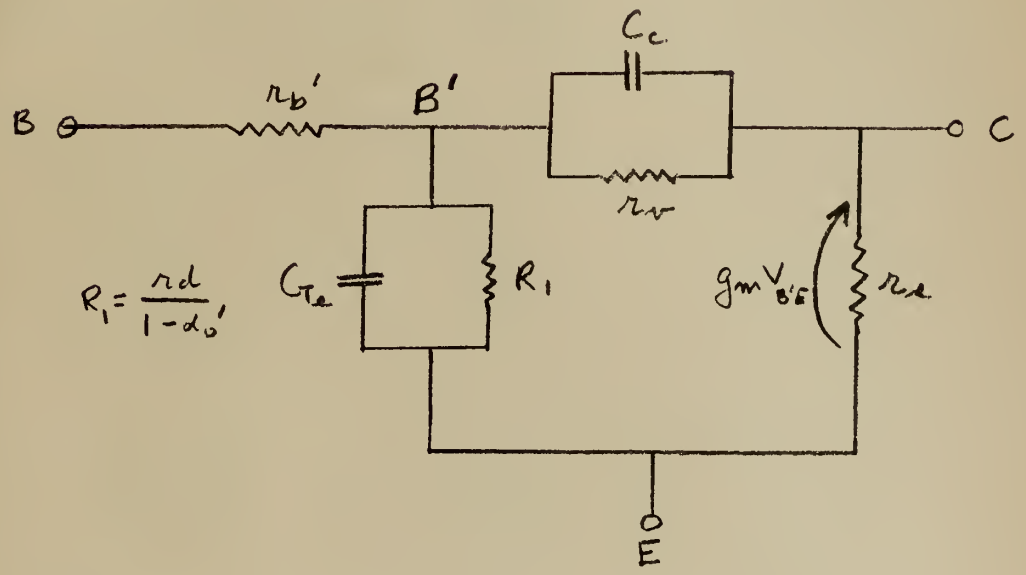
3) The emitter-base transition voltage, V_{eb}, is very low.

4) The diffusion capacitance must be very low to give a cut-off frequency of 2940 mc due to the diffusion process. Diffusion capacitance $\approx 1 \mu\mu f$.

APPENDIX III

DEVELOPMENT OF VALUES FOR LUMPED CONSTANTS SHOWN IN FIGURE 13

Figure 13 is reproduced below.



The value of resistor $R_1 = \frac{r_d}{1-\alpha_o'}$ is determined from the low-frequency value of input impedance when Experiment A is performed. At the half power frequency the reactance of C_{Te} equals the resistance R_1.

Therefore:

$$\frac{1}{2\pi f_{CB}' C_{Te}} = \frac{r_d}{1-\alpha_o'}$$

$$C_{Te} = \left(\frac{1-\alpha_o'}{r_d}\right)\left(\frac{1}{2\pi f_{CB}'}\right)$$

$$f_{c\beta} = f_{c\alpha}\,(1-\alpha_0')$$

Therefore

$$C_{Te} = \frac{1}{2\pi r_d f_{c\alpha}'}$$

To find the value of g_m,

$$\frac{g_m V_{B'E}}{\frac{V_{B'E}}{\left(\frac{r_d}{1-\alpha_0'}\right)}} = -\frac{\alpha_0'}{1-\alpha_0'}$$

$$\frac{g_m r_d}{1-\alpha_0'} = -\frac{\alpha_0'}{1-\alpha_0'}$$

Therefore

$$g_m = -\frac{\alpha_0'}{r_d}$$

Thesis
K24 28936
Keihner
A high frequency transistor
analysis.